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PLANT DESIGN AND ECONOMICS FOR CHEMICAL ENGINEERS

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BUILDING FOR THE FUTURE OF A PROFESSION

Fifteen prominent chemical engineers first met in New York more than thirty years ago to plan a continuing literature for their rapidly growing profession. From industry came such pioneer practitioners as Leo H. Baekeland, Arthur D. Little, Charles L. Reese, John V. N. Dorr, M. C. Whitaker, and R. S. McBride. From the universities came such eminent educators as William H. Walker, Alfred H. White, D. D. Jackson, J. H. James, J. F. Norris, Warren K. Lewis, and Harry A. Curtis. H. C. Parmelee, then editor of *Chemical & Metallurgical Engineering*, served as chairman and was joined subsequently by S. D. Kirkpatrick as consulting editor.

After several meetings, this Editorial Advisory Committee submitted its report to the McGraw-Hill Book Company in September, 1925. In it were detailed specifications for a correlated series of more than a dozen text and reference books, including a chemical engineers' handbook and basic textbooks on the elements and principles of chemical engineering, on industrial applications of chemical synthesis, on materials of construction, on plant design, on chemical engineering economics. Broadly outlined, too, were plans for monographs on unit operations and processes and on other industrial subjects to be developed as the need became apparent.

From this prophetic beginning has since come the McGraw-Hill Series in Chemical Engineering, which now numbers more than forty books. More are always in preparation to meet the ever growing needs of chemical engineers in education and in industry. In the aggregate these books represent the work of literally hundreds of authors, editors, and collaborators. But no small measure of credit is due the pioneering members of the original committee and those engineering educators and industrialists who have succeeded them in the task of building a permanent literature for the chemical engineering profession.

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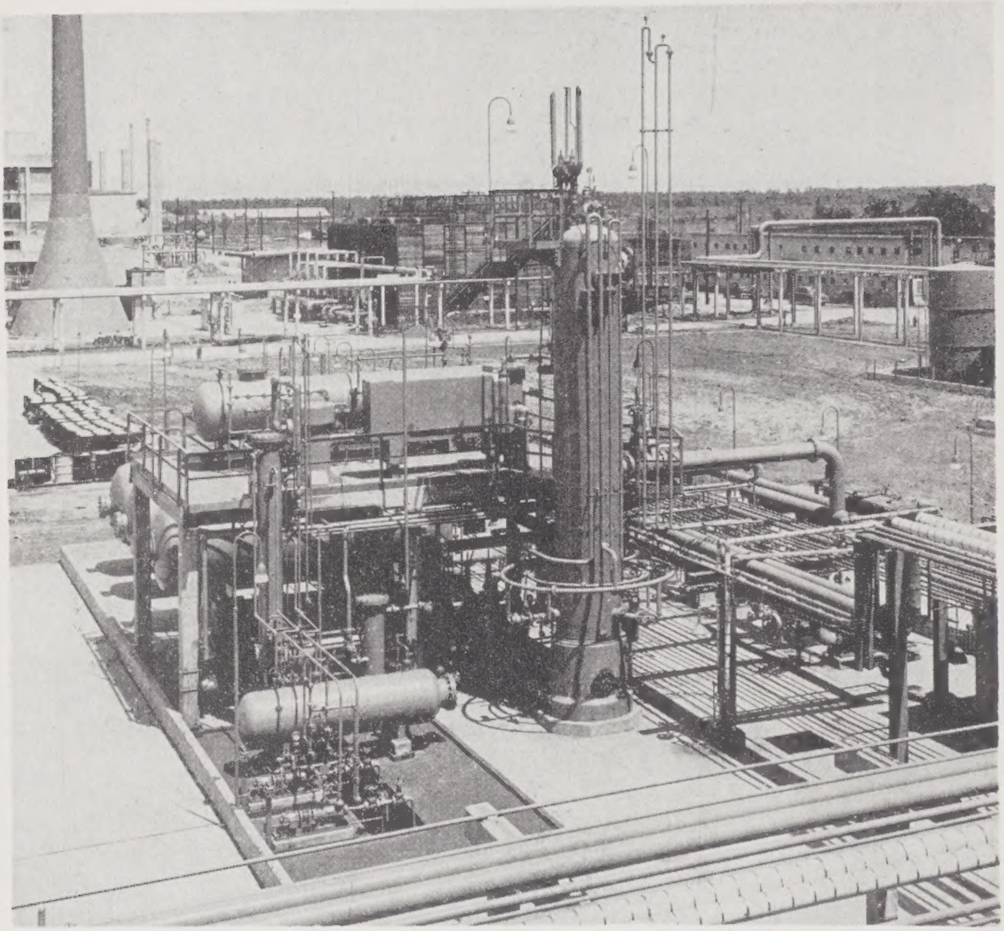

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The complete plant—the complete economic process. Here is the design engineer's goal. *(C. F. Braun and Co.)*

Plant Design and Economics for Chemical Engineers

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Registered Professional Engineer
Professor of Chemical Engineering
University of Illinois

McGRAW-HILL BOOK COMPANY, INC.
New York   Toronto   London
1958

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PLANT DESIGN AND ECONOMICS FOR CHEMICAL ENGINEERS

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PREFACE

The principles involved in the design of chemical plants and equipment are an essential part of chemical engineering. An understanding of these principles is a prerequisite for any successful chemical engineer, no matter whether his final position is in direct design work or in production, administration, sales, research, development, or any other related field.

The expression *plant design* immediately connotes industrial applications; consequently, the dollar sign must always be kept in mind when carrying out the design of a plant. The theoretical and practical aspects are important, of course; but, in the final analysis, the answer to the question "Will we realize a profit from this venture?" almost always determines the true value of the design. The chemical engineer, therefore, should consider plant design and applied economics as one combined subject.

The purpose of this book is to present economic and design principles as applied in chemical engineering processes and operations. No attempt is made to train the reader as a skilled economist, and, obviously, it would be impossible to present all the possible ramifications involved in the multitude of different plant designs. Instead, the goal has been to give a clear concept of the important principles and general methods. The subject matter and manner of presentation are such that the book should be of value to advanced chemical engineering undergraduates, graduate students, and practicing engineers. The information should also be of interest to administrators, operation supervisors, and research or development workers in the process industries.

The first part of the text deals with applied economics, with particular emphasis on economics in the process industries and in design work. The various costs involved in industrial processes, capital investments and investment returns, cost estimation, cost accounting, optimum economic design methods, and other subjects dealing with economics are covered both qualitatively and quantitatively. The remainder of the book deals with methods and important factors in the design of plants and equipment. Generalized subjects, such as waste disposal, structural design, and equipment fabrication, are included along with design methods for different types of process equipment. Basic cost data and cost correlations are also presented for use in making cost estimates.

Illustrative examples and sample problems are used extensively in the text to illustrate the applications of the principles to practical situations. Problems are included at the ends of most of the chapters to give the reader a chance to test himself as to his understanding of the material.

To simplify use of the cost data given in this book, all cost figures are presented for the date of Jan. 1, 1957. The construction cost index, as compiled by the *Engineering News-Record*, was used for converting all costs to the uniform basis. Since exact prices can be obtained only by direct quotations from manufacturers, caution should be exercised in the use of the data for other than approximate cost estimation purposes.

The book would be suitable for use in a one- or two-semester course for advanced undergraduate or graduate chemical engineers. It is assumed that the reader has a background in stoichiometry, thermodynamics, unit operations, and chemical technology as taught in the ordinary undergraduate programs in chemical engineering. Detailed explanations of the development of various design equations and methods are presented. The purpose of this is to show the reader the philosophy of design and to eliminate the concept that design is primarily number plugging in empirical equations.

Although nomographs, simplified equations, and shortcut methods are included, every effort has been made to indicate the theoretical background and assumptions for these relationships. The true value of plant design and economics for the chemical engineer is not found merely in the ability to put numbers in an equation and solve for a final answer. The true value is found in obtaining an understanding of the reasons *why* a given calculation method gives a satisfactory result. This understanding gives the engineer the confidence and ability necessary to proceed on his own when he encounters new problems for which there are no predetermined methods of solution. Thus, throughout the study of plant design and economics, the engineer should always attempt to understand the assumptions and theoretical factors involved in the various calculation procedures, and he should never allow himself to fall into the habit of robot-like number plugging.

Because applied economics and plant design deal with practical applications of chemical engineering principles, a study of these subjects offers an ideal way for tying together the entire field of chemical engineering. The final result of a plant design may be expressed in dollars and cents, but this result can only be achieved through the application of various theoretical principles combined with industrial and practical knowledge. Both theory and practice are emphasized in this book, and aspects of all phases of chemical engineering are included.

If the chemical engineer is to obtain the maximum benefit from this text, he must be prepared to make a concentrated study of the theories underlying economic and design principles. In this way, the applications will have a broad significance and the reader can obtain the over-all perspective required of a true chemical engineer.

The author is indebted to the many industrial firms and individuals who have supplied information and comments on the material presented in this book. In particular, the author wishes to express his appreciation to Robert B. Beckmann, Cecil H. Chilton, Harry G. Drickamer, John C. Garver, Thomas J. Hanratty, Julian C. Smith, and James W. Westwater for their constructive criticism and their many helpful suggestions.

MAX S. PETERS

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CHAPTER 1

INTRODUCTION

The value of a chemical engineer is determined by his ability to apply basic principles, facts, and methods in order to accomplish some useful purpose. In this modern age of industrial competition, the ultimate definition of a useful purpose can almost always be expressed on a tangible profit basis of dollars and cents. It is not sufficient, therefore, for a chemical engineer merely to have a knowledge and understanding of physics, chemistry, mathematics, mechanics, stoichiometry, thermodynamics, the unit operations, chemical technology, and other related scientific subjects; he must also have the ability to apply this knowledge to practical situations, and, in making these applications, he must recognize the importance of the dollar sign.

Plant design requires the use of engineering principles and theories combined with a practical realization of the limits imposed by industrial conditions. The development of a plant-design project involves a wide variety of talents. Research, market analyses, design of individual pieces of equipment, plant-location surveys, and many other problems are involved in the design of industrial plants.

Although the chemical engineer must understand the principles related to the various design phases, the individual parts of the design are of little benefit until they are combined to give one complete unit. The complete plant, the complete unit—here is the design engineer's goal. However, one major qualification must be added before the goal is attained. This is the qualification that the operation must be able to proceed economically. The design may be theoretically perfect and the final plant may be able to operate exactly as predicted, but this is of no value if it is impossible to make any profit with the proposed process. Thus, applied economics is an integral and essential part of plant design.* The design engineer must consider costs, investments, return on investments, and similar economic factors constantly from the time the initial project survey starts until the final plant is completed and in efficient operation.

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* To an engineer, the term *economics* (or, more properly, *applied economics*) refers to the analysis of all factors affecting costs and profits in industrial ventures. The related definition of *economics*, as interpreted by economists, is "the science that investigates the conditions and laws affecting the production, distribution, and consumption of wealth."

TEAMWORK AND THE OVER-ALL DESIGN PROJECT

As used in this book, the general term *plant design* includes all the engineering aspects involved in the development of a new industrial plant. Thus, the so-called "design engineer" refers to the engineer who may be making economic evaluations of new processes, designing individual pieces of equipment for a proposed plant, or developing a plant layout for coordination of the over-all operation. In many instances, the term *process engineering* is used in connection with economic evaluation and general economic analyses of industrial processes, while *process design* refers to the actual design of the equipment and facilities necessary for carrying out the process. Similarly, the meaning of plant design is limited by some engineers to items related directly to the complete plant, such as plant layout, general service facilities, and plant location.

The purpose of this book is to present the major aspects of plant design as related to the over-all design project. Although one man cannot be an expert in *all* the phases involved in plant design, he should be acquainted with the general problems and approach in each of the phases. The process engineer may not be connected directly with the final detailed design of the equipment, and the designer of the equipment may have little influence on a decision by management as to whether or not a given return on an investment is adequate to justify construction of a complete plant. Nevertheless, if the over-all design project is to be successful, close teamwork is necessary among the various groups of engineers working on the different phases of the project. The most effective teamwork and coordination of efforts are obtained when each of the engineers in the specialized groups is aware of the many functions in the *over-all* design project.

DEVELOPMENT OF THE DESIGN PROJECT

Many different steps are involved in the development of a design project. The first step must be the origination of the basic idea. This idea may occur spontaneously to someone who is acquainted with the aims and needs of a particular concern, or it may be the result of an orderly research program or an offshoot of such a program. Sometimes the idea for a design project may occur through a customer contact. The customer indicates a need for a special product as, for example, a solvent having a certain combination of properties. If the prospect sounds sufficiently promising, a research program and, ultimately, a complete design project may be launched to determine the advisability of producing the particular product.

Occasionally, the original idea may come from an accidental discovery, such as a broken thermometer leading to the discovery of the catalytic effect of mercury in an important chemical reaction.

If the initial analysis indicates that the idea may have possibilities of developing into a worthwhile project, a preliminary research or investigation program is initiated. Here, a general survey of the possibilities for a successful process is made considering the physical and chemical operations involved as well as the economic aspects. Next comes the process-research phase including preliminary market surveys, laboratory-scale experiments, and production of research samples of the final product. When the potentialities of the process are fairly well established, the project is ready for the development phase. At this point, a pilot plant or a commercial-development plant may be constructed. A pilot plant is a small-scale replica of the full-scale final plant, while a commercial-development plant is usually made from odd pieces of equipment which are already available and is not meant to duplicate the exact setup to be used in the full-scale plant.

Design data and other process information are obtained during the development stage. This information is used as the basis for carrying out the additional phases of the design project. A complete market analysis is made, and samples of the final product are sent to prospective customers to determine if the grade is satisfactory and if there is a reasonable sales potential. Capital-cost estimates for the proposed plant are made. Probable returns on the required investment are determined, and a complete cost-and-profit analysis of the process is developed.

If the economic picture is still satisfactory, the final process-design phase is ready to begin. All the design details are worked out in this phase including controls, services, piping layouts, firm price quotations, specifications and designs for individual pieces of equipment, and all the other design information necessary for the construction of the final plant. A complete construction design is then made with elevation drawings, plant-layout arrangements, and other information required for the actual construction of the plant. The final stage consists of procurement of the equipment, construction of the plant, start-up of the plant, over-all improvements in the operation, and development of standard operating procedures to give the best possible results.

The development of a design project proceeds in a logical, organized sequence requiring more and more time, effort, and expenditure as one phase leads into the next. It is extremely important, therefore, to stop and analyze the situation carefully before proceeding with each subsequent phase. Many projects are discarded as soon as the preliminary investigation or research on the original idea is completed. The design engineer must maintain a realistic and practical attitude in advancing through the various stages of a design project. He must not be swayed by his own personal interests and desires when he decides if further work on a particular project is justifiable. Remember, if the design engineer's work is continued on through the various phases of a design project, it will eventually end up in a proposal that money be invested in the process. If no tangible return can be realized from the investment, the proposal will be turned down. Therefore, the engineer should have the ability to eliminate unprofitable ventures before the design project approaches a final-proposal stage.

OPTIMUM DESIGN

In almost every case encountered by a design engineer, there are several alternative methods which can be used for any given process or operation. For example, formaldehyde can be produced by catalytic dehydrogenation of methanol, by controlled oxidation of natural gas, or by direct reaction between CO and H_2 under special conditions of catalyst, temperature, and pressure. Each of these processes contains many possible alternatives involving variables such as gas-mixture composition, temperature, pressure, and choice of catalyst. It is the duty of the design engineer to choose the best process and to incorporate into his design the equipment and methods which will give the best results.

It is easy to say we want the "best process" or the "best results," but it is necessary to analyze the meaning of these expressions. The design engineer ordinarily prefers to replace the word "best" by "optimum" and then add a designating qualification such as optimum economic design or optimum operation design.

Optimum Economic Design. If there are two or more methods for obtaining exactly equivalent final results, the preferred method would be the one involving the least total cost. This is the basis of an *optimum economic design*. One typical example of an optimum economic design is determining the pipe diameter to use when pumping a given amount of fluid from one point to another. Here the same final result (i.e., a set amount of fluid pumped between two given points) can be accomplished by using an infinite number of different pipe diameters. However, an economic balance will show that one particular pipe diameter gives the least total cost. The total cost includes the cost for pumping the liquid and the cost (i.e., fixed charges) for the installed piping system.

A graphical representation showing the meaning of an optimum economic pipe diameter is presented in Fig. 1-1. As shown in this figure, the pumping cost increases with decreased size of pipe diameter because of frictional effects, while the fixed charges for the pipeline become lower when smaller pipe diameters are used because of the reduced capital investment. The optimum economic diameter is found where the sum of the pumping costs and fixed costs for the pipeline becomes a minimum, since this represents the point of least total cost. In Fig. 1-1, this point is represented by E.

The design engineer often selects a final design on the basis of conditions giving the least total cost. In many cases, however, alternative designs do not give final products or results that are exactly equivalent. It then becomes necessary to consider the quality of the product or the operation as well as the total cost. When the engineer speaks of an optimum economic design, he ordinarily means the cheapest one out of a number of equivalent designs.

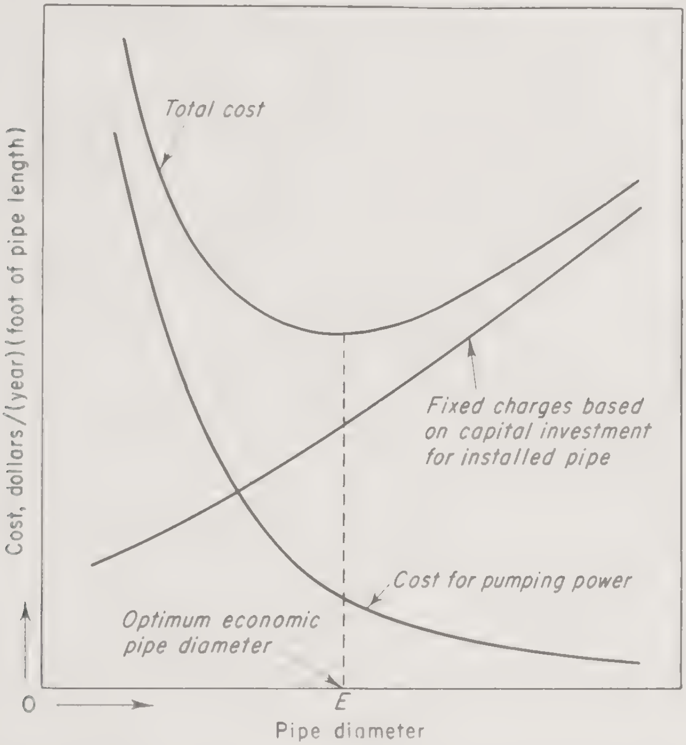

FIG. 1-1. Determination of optimum economic pipe diameter for constant mass-throughput rate.

Other types of optimum economic requirements are sometimes encountered by design engineers. For example, it may be desirable to choose a design which gives the maximum profit per unit of time or the minimum total cost per unit of production.

Optimum Operation Design. Many processes require definite conditions of temperature, pressure, contact time, or other variables if the best results are to be obtained. It is often possible to make a partial separation of these optimum conditions from direct economic considerations. In cases of this type, the best design is designated as the *optimum operation design*.

The design engineer should remember, however, that economic considerations ultimately determine most quantitative decisions. Thus, the optimum operation design is usually merely a tool or step in the development of an optimum economic design.

An excellent example of an optimum operation design is the determination of operating conditions for the catalytic oxidation of sulfur dioxide to sulfur trioxide. Suppose that all the variables, such as converter size, gas rate, catalyst activity, and entering-gas concentration, are fixed and the only possible variable is the temperature at which the oxidation occurs. If the temperature is too high, the yield of SO_3 will be low because the equilibrium between SO_3, SO_2, and O_2 is shifted in the direction of SO_2 and O_2. On the other hand, if the temperature is too low, the yield will be poor because the reaction rate between SO_2 and O_2 will be low. Thus, there must be one temperature where the amount of sulfur trioxide formed will be a maximum. This particular temperature would give the optimum operation design. Figure 1-2 presents a graphical method for determining the optimum operation temperature for the sulfur dioxide converter in this example. Line AB represents the maximum yields obtainable when the reaction rate is controlling, while line CD indicates the maximum yields on the basis of equilibrium conditions controlling. Point O represents the optimum operation temperature where the maximum yield is obtained.

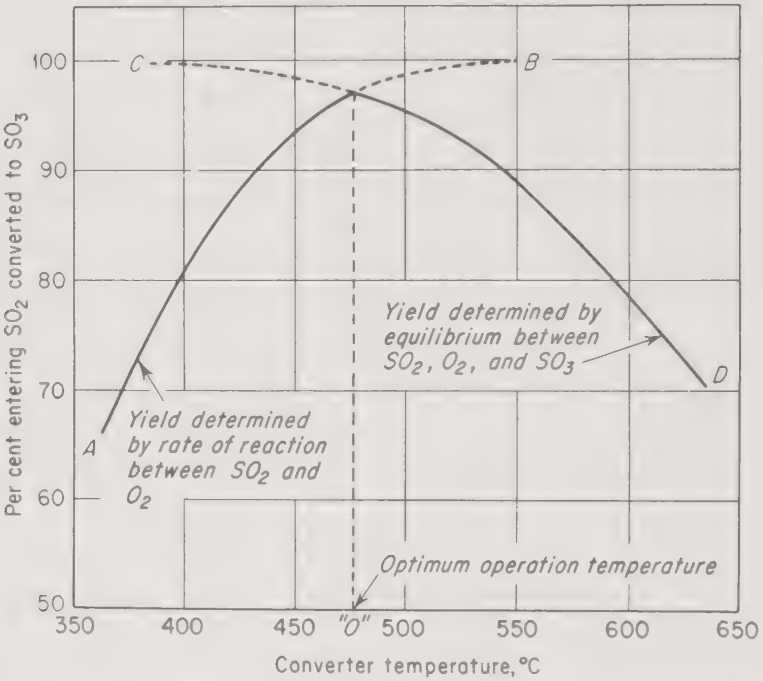

FIG. 1-2. Determination of optimum operation temperature in sulfur dioxide converter.

The preceding example is a simplified case of what a design engineer would encounter. In reality, it would usually be necessary to consider various converter sizes and operation with a series of different temperatures in order to arrive at the optimum operation design. Under these conditions, several equivalent designs would apply, and the final decision would be based on the optimum economic conditions for the equivalent designs.

PRACTICAL CONSIDERATIONS IN DESIGN

The design engineer must never lose sight of the practical limitations involved in the applications of his work. It may be possible to determine an exact pipe diameter for an optimum economic design, but this does not mean that this exact size must be used in the final design. Suppose the optimum diameter were 3.43 in. It would be impractical to have a special pipe fabricated with an inside diameter of 3.43 in. Instead, the engineer would choose a standard pipe size which could be purchased at regular market prices. In this case, the recommended pipe size would probably be standard 3½-in.-diameter pipe having an inside diameter of 3.55 in.

If the design engineer happened to be very conscientious and worried constantly about getting an adequate return on all investments, he might say, "A standard 3-in.-diameter pipe would require less investment and would probably only increase the total cost slightly; therefore, I think we should compare the costs with a 3-in. pipe to the costs with the 3½-in. pipe before making a final decision." Theoretically, the conscientious engineer is correct in this case. Suppose the total cost of the installed 3½-in. pipe is $5000 and the total cost of the installed 3-in. pipe is $4500. If the total yearly savings on power and fixed charges, using the 3½-in. pipe instead of the 3-in. pipe, were $25, the yearly per cent return on the extra $500 investment would be only 5 per cent. Since it should be possible to invest money in other interests to give more than a 5 per cent return, it would appear that the 3-in.-diameter pipe would be preferred over the 3½-in.-diameter pipe.

The logic presented in the preceding example is perfectly sound. It is a typical example of investment comparison and should be understood by all design engineers. However, the engineer must be practical in developing a design. Even though the optimum economic diameter was 3.43 in., the good design engineer knows that this diameter is only an exact mathematical number and may vary from month to month as prices or operating conditions change. Therefore, all he expects to obtain from this particular optimum economic calculation is a good estimation as to the best diameter, and investment comparisons may not be necessary.

The practical design engineer understands the physical problems which are involved in the final operation and maintenance of the designed equipment. In developing the plant layout, crucial control valves must be placed where they are easily accessible to the operators. Sufficient space must be available for maintenance men to check, take apart, and repair equipment. The engineer should realize that cleaning operations are simplified if a scale-forming fluid is passed through the inside of the tubes rather than on the shell side of a tube-and-shell heat exchanger. Obviously, then, sufficient plant-layout space should be made available so that the maintenance men can remove the head of the installed exchanger and force cleaning worms or brushes through the inside of the tubes. Similarly, space should be available for removing the entire tube bundle when necessary.

The theoretical design of a distillation unit may indicate that the feed should be introduced on one particular tray in the tower. Instead of specifying a tower with only one feed inlet on the calculated tray, the practical engineer will also include inlets on several trays above and below the calculated feed point. He knows the actual operating conditions for the tower will vary, and he knows the assumptions included in his calculations make it impossible to guarantee absolute accuracy.

The preceding examples typify the type of practical problems the design engineer encounters. In design work, theoretical and economic principles must be combined with an understanding of the common practical problems that will arise when the process finally comes to life in the form of a complete plant or a complete unit.

COST ESTIMATION

At periodic intervals during the course of a plant design, the economic potentialities of the process must be evaluated. When the final process-design stage is completed, it is possible to make accurate cost estimations because detailed equipment specifications and definite plant-facility information are available. Direct price quotations based on the detailed specifications can then be obtained from various manufacturers. However, no design project should proceed to the final stages before costs are considered, and cost estimates should be made throughout all the early stages of the design when complete specifications are not available. Evaluation of costs in the preliminary design phases is sometimes called "guesstimation" or "horse-back estimation," but the appropriate designation is *predesign cost estimation.*

The design engineer must be certain to consider all possible factors when making a cost analysis. He must include fixed costs, such as rent, insurance, taxes, and depreciation. Direct production costs for raw materials, labor, maintenance, power, and utilities must also be included along with costs for plant and administrative overhead, distribution of the final products, and other miscellaneous items.

Many special techniques have been developed for making accurate cost estimations. Labor and material indexes, standard cost ratios, and special multiplication factors are examples of information used when making design estimates of costs. The final test as to the validity of any cost estimation can come only when the completed plant has been put into operation. However, if the design engineer is well acquainted with the various estimation methods and their accuracy, it is possible to make remarkably close cost estimations even before the final process design gives detailed specifications.

THE DESIGN APPROACH

The general approach in any plant design involves a carefully balanced combination of theory, practice, and plain common sense. In original design work, the engineer must deal with many different types of experimental and empirical data. He may be able to obtain accurate values of heat capacity, density, vapor-liquid equilibrium data, or other information on physical properties from the literature. In many cases, however, exact values for necessary physical properties are not available, and the engineer is forced to make approximate estimations of these values. Many approximations also must be made in carrying out theoretical design calculations. For example, even though the engineer knows that the perfect-gas law applies exactly only to simple gases at very low pressures, he is willing to use this law in many of his calculations when the gas pressure is as high as 5 or more atmospheres. With common gases, such as air or simple hydrocarbons, the error introduced by using the perfect-gas law at ordinary pressures and temperatures is usually negligible in comparison with other uncertainties involved in design calculations. The engineer prefers to accept this error rather than waste his time determining virial coefficients or other factors to correct for perfect-gas deviations.

In the engineer's approach to any design problem, he must be prepared to make many assumptions. Sometimes these assumptions are made because no absolutely accurate values or methods of calculation are available. At other times, methods involving close approximations are used because exact treatments would require long and laborious calculations giving little gain in accuracy. The good design engineer recognizes the need for making certain assumptions in his work, but he knows that this type of approach introduces some uncertainties into his final results. Therefore, assumptions are made only when they are necessary and essentially correct.

Another important factor in the approach to any design problem involves economic conditions and limitations. The engineer must consider costs and probable profits constantly throughout all his work. It is almost always better to sell many units of a product at a low profit per unit than a few units at a high profit per unit. Consequently, the engineer must take the volume of production into account when determining costs and total profits for various types of designs. This obviously leads to considerations of customer demands. What type of product does the customer want? How can we induce him to buy large amounts of our product? These factors may appear to be distantly removed from the drawing table of a design engineer, but they are extremely important in determining the ultimate success of a plant design.

Theoretical understanding, comprehension of practical and economic limitations, common sense, ability to do original and hard work—these are the requirements for a good design engineer, and they must be used in the approach to any design problem.

CHAPTER 2

COSTS IN CHEMICAL PROCESSES

Because of the necessity for combining economic considerations with plant design, the design engineer must be aware of the many different types of costs involved in manufacturing processes. Money must be paid out for direct plant expenses, such as those for raw materials, labor, and equipment. In addition, many other indirect expenses are incurred, and these must be included if a complete analysis of the total cost is to be obtained. Some examples of these indirect expenses are administrative salaries, product-distribution costs, and costs for interplant communications.

A plant design must present a process that is capable of operating under conditions which will yield a profit. Since net profit equals total income minus *all* expenses, it is essential to include *all* costs when making a profit analysis. The costs involved in manufacturing processes may be divided into the two categories of *factory manufacturing costs* and *general expenses.*

When determining gross earnings, it is not necessary to include income taxes as an expense; however, when considering net profits, the expenses due to income taxes are extremely important, and this cost must be included as a special type of general expense.

A capital investment is required for any industrial process, and determination of the necessary investment is an important part of a plant-design project. The total investment for any process consists of the fixed-capital investment for the physical equipment and facilities in the plant plus the working capital for money which must be available to pay salaries, keep raw materials and products on hand, and handle other special items requiring a direct cash outlay. Thus, in an analysis of costs in industrial processes, investment costs, factory manufacturing costs, and general expenses including income taxes must be taken into consideration.

BREAKDOWN OF COSTS

Factory Manufacturing Costs. All expenses directly connected with the manufacturing operation or the physical equipment of the factory itself are included in factory manufacturing costs. These expenses may be divided into three classifications as follows: (1) fixed charges, (2) direct production costs, and (3) plant-overhead expenses.

Fixed charges are expenses which remain practically constant from year to year and do not vary widely with changes in production rate. Depreciation, taxes, insurance, and rent require expenditures that can be classified as fixed charges.

Direct production costs include expenses directly connected with the manufacturing operation. This type of cost involves expenditures for raw materials (including transportation, unloading, etc.); direct operating labor; supervisory and clerical labor directly connected with the manufacturing operation; plant maintenance and repairs; operating supplies such as oil, grease, and janitor supplies; power; utilities; and patent royalties.

Plant-overhead costs are for hospital and medical services; general plant maintenance and overhead; safety services; payroll overhead including pensions, vacation allowances, social security, and life insurance; packaging, restaurant and recreation facilities, salvage services, control laboratories, property protection, plant superintendence, warehouse and storage facilities, and special employee benefits. These costs are similar to the basic fixed charges in that they do not vary widely with changes in production rate.

General Expenses. In addition to the factory manufacturing costs, other general expenses are involved in any company's operations. These general expenses may be classified as (1) administrative expenses, (2) distribution and selling expenses, (3) research and development expenses, (4) financing expenses, and (5) gross-earnings expenses.

Administrative expenses include costs for executive and clerical wages, office supplies, upkeep on office buildings, and general communications.

Distribution and selling expenses are costs incurred in the process of selling and distributing the various products. These costs include expenditures for sales offices, salesmen, shipping, and advertising.

Research and development expenses are incurred by any progressive concern which wishes to remain in a competitive industrial position. These costs are for salaries, wages, special equipment, research facilities, and consultant fees related to developing new ideas or improved processes.

Financing expenses include the extra costs involved in procuring the money necessary for the capital investment. Financing expense is usually limited to interest on borrowed money, and this expense is sometimes listed as a fixed charge.

Gross-earnings expenses are based on income-tax laws. These expenses are a direct function of the gross earnings made by all the various interests held by the particular company. Because these costs depend on the company-wide picture, they are often not included in predesign or preliminary cost-estimation figures for a single plant, and the probable returns are reported as the gross earnings obtainable with the given plant design.

Raw materials		Direct production costs	Factory manufacturing costs	Total product cost
Operating labor				
Operating supervision				
Maintenance and repairs				
Operating supplies				
Steam	Power and utilities			
Electricity				
Fuel				
Refrigeration				
Water				
Royalties (if not on lump-sum basis)				
Rent		Fixed charges		
Insurance				
Taxes (property)				
Depreciation				
Medical		Plant overhead costs		
Safety and protection				
General plant overhead				
Payroll overhead				
Packaging				
Restaurant				
Recreation				
Salvage				
Control laboratories				
Plant superintendence				
Storage facilities				
Executive salaries		Administrative expenses	General expenses	
Clerical wages				
Office supplies				
Communications				
Sales offices		Distribution and selling expenses		
Salesmen expenses				
Shipping				
Advertising				
Research and development				
Financing (interest) (often considered a fixed charge)				

Total income − total product cost = gross earnings
Gross earnings − income taxes = net profit

FIG. 2-1. Costs involved in chemical manufacturing operations.

Total Product Cost. The sum of factory manufacturing costs and general expenses represents the total expenditure. Since all these costs are necessary to make the production of the final product completely successful from *all* viewpoints, the sum of factory manufacturing costs and general expenses is designated as *total product cost.*

A tabular representation showing the various types of costs involved in chemical manufacturing processes is presented in Fig. 2-1.

FACTORS AFFECTING COSTS

When a design engineer determines costs for any type of commercial process, he wants these costs to be as accurate as possible. To accomplish this, the engineer must have a complete understanding of the many factors that can affect costs. For example, many companies have reciprocal arrangements with other concerns whereby certain raw materials or types of equipment may be purchased at prices lower than the prevailing market prices. Therefore, if the design engineer bases the cost of the raw materials for his process on regular market prices, he may find that the process is uneconomical. If the engineer had based his estimate on the actual prices his company would have to pay for the raw materials, the economic picture might have been altered completely. The design engineer must keep up to date on price fluctuations, company policies, governmental regulations, and other factors affecting costs.

Operating Time and Rate of Production. One of the factors that has an important effect on costs is the fraction of the total available time during which the process is in operation. When equipment stands idle for an extended period of time, the labor costs are usually low; however, other costs, such as those for maintenance, protection, and depreciation, continue even though the equipment is not in active use.

Operating time, rate of production, and sales demand are closely interrelated. The ideal plant should operate under a time schedule which gives the maximum production rate while maintaining economic operating methods. In this way, the total cost per unit of production is kept near a minimum because the fixed costs are utilized to the fullest extent. This ideal method of operation is based on the assumption that the sales demand is sufficient to absorb all the material produced. If the production capacity of the process is greater than the sales demand, the operation can be carried on at reduced capacity or periodically at full capacity.

Figure 2-2 gives a graphical analysis of the effect on costs and profits when the rate of production varies. As indicated in this figure, the fixed costs remain constant and the total product cost increases as the rate of production increases. The point where the total product cost equals the total income is known as the *break-even point.* Under the conditions shown in Fig. 2-2, an ideal production rate for the chemical processing plant would be approximately 450,000 lb month, because this represents the point of maximum earnings.

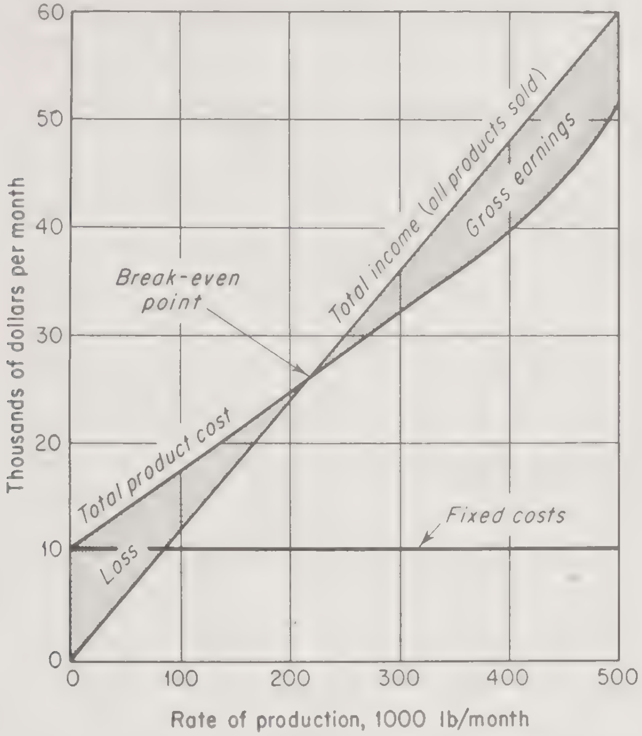

FIG. 2-2. Break-even chart for chemical processing plant.

The effects of production rate and operating time on costs should be recognized by the design engineer. By considering sales demand along with the capacity and operating characteristics of the equipment, the engineer can recommend the production rates and operating schedules that will give the best economic results.

Company Policies. Policies of individual companies have a direct effect on costs. For example, some concerns have particularly strict safety regulations and these must be met in every detail. The purchasing office may have special agreements permitting some raw materials or equipment to be purchased at reduced prices. Accounting procedures and methods for determining depreciation costs vary among different companies. The company policies with reference to labor unions should be considered, because these will affect overtime labor charges and the type of work the operators or other employees can do. Labor-union policies may even dictate the amount of wiring and piping that can be done on a piece of equipment before it is brought into the plant and, thus, have a direct effect on the total cost of installed equipment.

The preceding are just a few of the many ways in which company policies can affect costs. Each concern has its own rules and regulations, and the design engineer should familiarize himself with these before he makes any final cost decisions.

Sources of Equipment. One of the major costs involved in any chemical process is for the equipment. In many cases, standard types of tanks, reactors, or other equipment are used, and a substantial reduction in cost can be made by employing idle equipment or by purchasing second-hand equipment. If new equipment must be bought, several independent quotations should be obtained from different manufacturers. When the specifications are given to the manufacturers, the chances for a low cost estimate are increased if the engineer does not place overly strict limitations on the design.

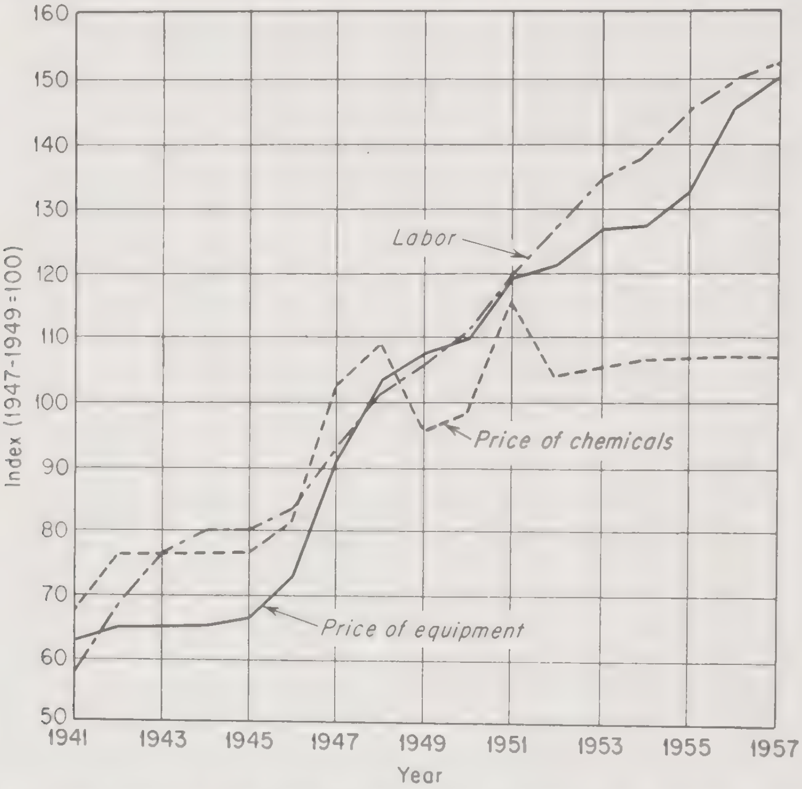

Fig. 2-3. Comparison of cost factors for chemical industry from 1941 to 1957. (*U.S. Bureau of Labor Statistics.*)

Price Fluctuations. In our modern economic society, prices may vary widely from one period to another, and this factor must be considered when the costs for an industrial process are determined. It would obviously be ridiculous to assume that plant operators or supervisors could be hired at the same wage rate in 1957 as in 1932. The same statement applies to comparing prices of equipment purchased at different times. The design engineer, therefore, must keep up to date on price and wage fluctuations. One of the most complete sources of information on existing price conditions is the *Monthly Labor Review* published by the U.S. Bureau of Labor Statistics. This publication gives up-to-date information on present prices and wages for different types of industries.

Figure 2-3 is a graphical representation showing the tremendous variations with time of prices and wages in the United States. This plot applies in particular to the chemical industry, but the same type of fluctuations has occurred throughout the entire industrial field.

Governmental Policies. The national government has many regulations and restrictions which have a direct effect on industrial costs. Some examples of these are import and export tariff regulations, restrictions on permissible depreciation rates, and income-tax regulations.

Prior to 1951, there were strict governmental regulations against rapid depreciation write-offs for industrial equipment. These restrictions increased the income-tax load for new companies during their first few years of existence and tended to discourage new enterprise. Therefore, during the Korean War, a fast amortization policy for certain defense installations was authorized. This policy permitted at least part of the value of the installation to be written off in 5 years as compared to an average of 10 to 15 years under the old laws. In 1954, a new law was passed permitting approximately two-thirds of the total investment for any process to be written off as depreciation during the first half of the useful life. A rapid write-off of this type is very desirable for some concerns because it reduces income taxes during the early years of the plant life.

Governmental policies with reference to capital gains and gross-earnings taxes should be understood when costs are determined. Suppose a concern decides to sell some valuable equipment before its useful life is over. The equipment has a certain asset or unamortized value, but the offered price may be more than the unamortized value. The profit over the unamortized value is taxable as capital gain at 25 per cent. If a fast depreciation method had been used, the capital gain would have been fairly large; however, this gain would be taxed at only 25 per cent, while the amount saved through fast-depreciation allowances may have been at an income-tax rate of over 50 per cent.*

The preceding example shows why the design engineer should understand the effects of governmental regulations on costs. Each company has its own methods for meeting these regulations, but changes in the laws and alterations in the national and company economic situation require constant surveillance if optimum cost conditions are to be maintained.

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* For a discussion of income-tax rates, see Chap. 4 (Taxes and Insurance).

CAPITAL INVESTMENTS

Before an industrial plant can be put into operation, a large amount of money must be supplied to purchase and install the necessary machinery and equipment. Land and service facilities must be obtained, and the plant must be erected complete with all piping, controls, and services. In addition, it is necessary to have money available for the payment of expenses involved in the plant operation.

The capital needed to supply the necessary manufacturing and plant facilities is called the *fixed-capital investment*, while that necessary for the operation of the plant is termed the *working capital*. The sum of the fixed-capital investment and the working capital is known as the *total capital investment*. The fixed-capital portion may be further subdivided into *manufacturing fixed-capital investment* and *nonmanufacturing fixed-capital investment*.

Fixed-capital Investment. Manufacturing fixed-capital investment represents the capital necessary for the production machinery and equipment, installed with all necessary auxiliaries and ready for operation. Expenses for piping, instruments, insulation, foundations, and site preparation are typical examples of costs included in the manufacturing fixed-capital investment.

Fixed capital required for construction overhead and for all plant components that are not directly related to the process operation is designated as the nonmanufacturing fixed-capital investment. These plant components include the land, processing buildings, administrative and other offices, warehouses, laboratories, transportation, shipping, and receiving facilities, utility and waste-disposal facilities, shops, and other permanent parts of the plant. The construction overhead cost consists of field-office and supervision expenses, home-office expenses, engineering expenses, miscellaneous construction costs, contractor's fees, and contingencies. In some cases, construction overhead is proportioned between manufacturing and nonmanufacturing fixed-capital investment.

Relative Magnitudes of Costs for Items Included in Fixed-capital Investment. A general idea as to the magnitude of the costs for the various items comprising the fixed-capital investment can be obtained from Table 1. The values presented in this table are approximations for ordinary chemical plants and will vary with different types of plants and localities.*

Working Capital. The working capital for an industrial plant consists of the total amount of money invested in (1) raw materials and supplies carried in stock, (2) finished products in stock and semifinished products in the process of being manufactured, (3) accounts receivable, and (4) cash

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* See Chap. 7 (Cost Estimation) for a detailed discussion on methods for estimating capital investments.

TABLE 1. RELATIVE MAGNITUDE OF COSTS FOR ITEMS INCLUDED IN FIXED-CAPITAL INVESTMENT *

Item	Per cent of fixed-capital investment for		
	Solid-processing plant	Solid-fluid-processing plant	Fluid-processing plant
Process equipment (delivered but not installed)	30	26	20
Process equipment (installed—includes equipment and auxiliaries, site preparation, foundations, supports, frames, platforms, insulation, painting, instrumentation, sewers, drains, erection, testing, etc.)	43	37	29
Piping	4	9	17
Manufacturing fixed-capital investment	47	46	46
Auxiliary components (includes process buildings, land, offices, warehouses, laboratories, transportation and utilities facilities, electrical installations, yard improvements, etc.)	26 †	26 †	23 †
Construction overhead (includes field and home office, supervision, engineering, insurance, etc.)	9	10	13
Contractor's fees	6	6	6
Contingencies	12	12	12
Nonmanufacturing fixed-capital investment	53	54	54

* These percentages apply for major additions to a plant at an existing site.

† For a new plant at a completely undeveloped site, the relative cost for auxiliary components is usually much greater than indicated here.

which must be kept on hand for monthly payment of operating expenses, such as salaries, wages, and raw-material purchases.

The raw-materials inventory included in working capital usually amounts to a 1-month supply of the raw materials valued at delivered prices. Finished products in stock and semifinished products have a value approximately equal to the total manufacturing cost for 1 month's production. Because credit terms extended to customers are usually based on an allowable 30-day payment period, the working capital required for accounts receivable ordinarily amounts to the production cost for 1 month of operation.

The ratio of working capital to total capital investment varies with different companies, but most chemical plants use an initial working capital amounting to 10 to 20 per cent of the total capital investment. This percentage may increase to as much as 50 per cent or more for companies producing products of seasonal demand because of the large inventories which must be maintained for appreciable periods of time.

FIXED CHARGES

Certain expenses are always present in an industrial plant whether or not the manufacturing process is in operation. Costs that are invariant with the amount of production are designated as *fixed costs* or *fixed charges*. These include costs for depreciation, local property taxes, insurance, and rent. Expenses of this type are a direct function of the capital investment. As a rough approximation, these charges amount to about 10 to 20 per cent of the total product cost.

Depreciation. Equipment, buildings, and other material objects comprising a manufacturing plant require an initial investment which must be written off as a manufacturing expense. In order to write off this cost, a decrease in value is assumed to occur throughout the useful life of the material possessions. This decrease in value is designated as *depreciation*.

Since depreciation rates are very important in determining the amount of income tax, the U.S. Bureau of Internal Revenue has established allowable depreciation rates based on the probable useful life of various types of equipment and other fixed items involved in manufacturing operations. While several alternative methods may be used for determining the rate of depreciation, a straight-line method is usually assumed for engineering projects. In applying this method, a useful-life period and a salvage value at the end of the useful life are assumed, with due consideration being given to possibilities of obsolescence and economic changes. The difference between initial cost and the salvage value divided by the total years of useful life gives the annual cost due to depreciation.

The annual depreciation rate for machinery and equipment ordinarily is about 10 per cent of the fixed-capital investment, while buildings are usually depreciated at an annual rate of about 3 per cent of the initial cost.

Local Taxes. The magnitude of local property taxes depends on the particular locality of the plant and the regional laws. Annual property taxes for plants in highly populated areas are ordinarily in the range of 2 to 4 per cent of the fixed-capital investment. In less populated areas, local property taxes are about 1 to 2 per cent of the fixed-capital investment.

Insurance. Insurance rates depend on the type of process being carried out in the manufacturing operation and on the extent of available protection facilities. On an annual basis, these rates amount to about 1 per cent of the fixed-capital investment.

Rent. Annual costs for rented land and buildings amount to about 8 to 10 per cent of the value of the rented property.

DIRECT PRODUCTION COSTS

Raw Materials. In the chemical industry, one of the major costs in a production operation is for the raw materials involved in the process. The amount of the raw materials which must be supplied per unit of time or per unit of product can be determined from process material balances. In many cases, certain materials act only as an agent of production and may be recoverable to some extent. Therefore, the cost should be based only on the amount of raw materials actually consumed as determined from the over-all material balances.

Direct price quotations from prospective suppliers are preferable to published market prices. For preliminary cost analyses, market prices are often used for estimating raw-material costs. These values are published regularly in journals such as the *Oil, Paint, and Drug Reporter* or quarterly in *Chemical and Engineering News.*

Freight or transportation charges should be included in the raw-material costs, and these charges should be based on the form in which the raw materials are to be purchased for use in the final plant. Although bulk shipments are cheaper than smaller-container shipments, they require greater storage facilities and inventory. Consequently, the demands to be met in the final plant should be considered when deciding on the cost of raw materials.

The ratio of the cost of raw materials to total plant cost obviously will vary considerably for different types of plants. In chemical plants, raw-material costs are usually in the range of 10 to 50 per cent of the total product cost.

Operating Labor. In general, operating labor may be divided into the two classes of skilled and unskilled labor. Hourly wage rates for operating labor in different industries at various locations can be obtained from the U.S. Bureau of Labor *Monthly Labor Review.* These rates may vary from $1 to over $3 per hour depending on the degree of skill involved and on local economic conditions. For chemical processes, operating labor usually amounts to about 15 per cent of the total product cost.

Direct Supervisory and Clerical Labor. A certain amount of direct supervisory and clerical labor is always required for a manufacturing operation. The necessary amount of this type of labor is closely related to the total amount of operating labor, complexity of the operation, and product quality standards. The cost for direct supervisory and clerical labor averages about 15 per cent of the cost for operating labor.

Utilities. The cost for utilities, such as steam, electricity, process and cooling water, compressed air, natural gas, and fuel oil, varies widely depending on the amount of consumption, plant location, and source. The utility may be purchased at predetermined rates from an outside source, or the service may be produced by the company's facilities. If the company supplies its own service and it is utilized for just one process, the entire cost of the service installation is usually charged to the manufacturing process. If the service is utilized for the production of several different products, the service cost is divided among the different products at a rate based on the amount of individual consumption.

Steam requirements include the amount consumed in the manufacturing process plus that necessary for building heat. An allowance for radiation and line losses must also be made.

Electrical power must be supplied for lighting, motors, and various process-equipment demands. These direct-power requirements should be increased by a factor of 1.1 to 1.25 to allow for line losses and contingencies. As a rough approximation, utility costs for ordinary chemical processes amount to 10 to 20 per cent of the total product cost.

Maintenance and Repairs. A considerable amount of expense is necessary for maintenance and repairs if a plant is to be kept in efficient operating condition. These expenses include the cost for labor, materials, and supervision.

Annual costs for equipment maintenance and repairs may range from as low as 2 per cent of the equipment cost if service demands are light to 20 per cent for cases in which there are severe operating demands. Charges of this type for buildings average 3 to 4 per cent of the building cost. In the process industries, the total plant cost per year for maintenance and repairs is roughly equal to an average of 6 per cent of the fixed-capital investment.

Operating Supplies. In any manufacturing operation, many miscellaneous supplies are needed to keep the process functioning efficiently. Items such as charts, lubricants, janitor supplies, test chemicals, and similar supplies cannot be considered as raw materials or maintenance and repair materials, and they are classified as operating supplies. The annual cost for this type of supplies is about 15 per cent of the total cost for maintenance and repairs.

Patents and Royalties. Many manufacturing processes are covered by patents, and it may be necessary to pay a set amount for patent rights or a royalty based on the amount of material produced. Even though the company involved in the operation obtained the original patent, a certain amount of the total expense involved in the development and procurement of the patent rights should be borne by the plant as an operating expense. In cases of this type, these costs are usually amortized over the legally protected life of the patent. A rough approximation of patent and royalty costs for patented processes is 2 to 6 per cent of the total product cost.

PLANT-OVERHEAD COSTS

The costs considered in the preceding sections are directly connected with the production operation. In addition, however, many other expenses are always involved if the complete plant is to function as an efficient unit. The expenditures required for routine plant services are included in *plant-overhead costs*. Nonmanufacturing machinery, equipment, and buildings are necessary for many of the general plant services, and the fixed charges and direct costs for these items are part of the plant-overhead costs.

Expenses connected with the following comprise the bulk of the charges for plant overhead:

Hospital and medical services
General engineering
Safety services
Cafeteria and recreation facilities
General plant maintenance and overhead
Payroll overhead including employee benefits
Control laboratories
Packaging
Plant protection
Janitor and similar services
Employment offices
Distribution of utilities
Shops
Lighting
Interplant communications and transportation
Warehouses
Shipping and receiving facilities

These charges are closely related to the costs for all labor directly connected with the production operation. The plant-overhead cost for chemical plants is about 50 to 70 per cent of the total expense for operating labor, supervision, and maintenance.

ADMINISTRATIVE COSTS

The expenses connected with top-management or administrative activities cannot be charged directly to manufacturing costs; however, it is necessary to include the *administrative costs* if the economic analysis is to be complete. Salaries and wages for administrators, secretaries, accountants, stenographers, typists, and similar workers are part of the administrative expenses, along with costs for office supplies and equipment, outside communications, administrative buildings, and other overhead items connected with administrative activities. These expenses amount to about 15 per cent of the cost for operating labor, supervision, and maintenance.

DISTRIBUTION AND SELLING COSTS

From a practical viewpoint, no manufacturing operation can be considered a success until the products have been sold or put to some profitable use. It is necessary, therefore, to consider the expenses involved in selling the products. Included in this category are salaries, wages, supplies, and other expenses for sales offices; salaries, commissions, and traveling expenses for salesmen; shipping expenses; and advertising expenses.

Distribution and selling costs vary widely for different types of plants depending on the particular material being produced, other products sold by the company, plant location, and company policies. These costs for most chemical plants are in the range of 2 to 20 per cent of the total product cost.

RESEARCH AND DEVELOPMENT COSTS

New methods and products are constantly being developed in the chemical industries. These accomplishments are brought about by emphasis on research and development. *Research and development costs* include salaries and wages for all personnel directly connected with this type of work, fixed and operating expenses for all machinery and equipment involved, costs for materials and supplies, direct overhead expenses, and miscellaneous costs. In the chemical industry, these costs amount to about 2 to 5 per cent of every sales dollar.

FINANCING

Interest. *Interest* is considered to be the compensation paid for the use of borrowed capital. A fixed rate of interest is established at the time the capital is borrowed; therefore, interest is a definite cost if it is necessary to borrow the capital used to make the investment for a plant. Although interest on borrowed capital is a fixed charge, there are many persons who claim that interest should not be considered as a manufacturing cost. It is preferable to separate interest from the other fixed charges and list it as a separate expense under the general heading of management or financing cost. Annual interest rates amount to 3 to 6 per cent of the total value of the borrowed capital.

When the capital investment is supplied directly from the existing funds of a company, it is a debatable point whether interest should be charged as a cost. For income-tax calculations, interest on owned money cannot be charged as a cost. In design calculations, however, interest can be included as a cost unless there is assurance that the total capital investment will be supplied from the company's funds and the company policies permit exclusion of interest as a cost.

GROSS-EARNINGS COSTS

The total income minus the total production cost gives the *gross earnings* made by the particular production operation. Because of income-tax demands, the final net profit is often much less than the gross earnings. Income-tax rates are based on the gross earnings received from all the company interests. Consequently, the magnitude of these costs varies widely from one company to another.

On an annual basis, the corporate income-tax laws for the United States in 1956 required payment of a 30 per cent normal tax on the complete gross earnings of a corporation plus a 22 per cent surtax on gross earnings above $25,000. This means that gross-earnings costs in 1956 could have amounted to 52 per cent of all earnings above $25,000 per year plus 30 per cent of the first $25,000. In addition, if other levies, such as regional income taxes, were included, the over-all tax rate could have been even higher.

CONTINGENCIES

Unforeseen events, such as strikes, storms, floods, price variations, and other *contingencies*, may have an effect on the costs for a manufacturing operation. When the design engineer predicts total costs, he often finds it advisable to take these factors into account. This can be accomplished by including a contingency factor equivalent to 1 to 5 per cent of the total product cost.*

PROBLEMS

1. A reactor of special design is the major item of equipment in a small chemical plant. The initial cost of the completely installed reactor is $60,000, and the salvage value at the end of the useful life is estimated to be $10,000. Excluding depreciation costs for the reactor, the total annual expenses for the plant are $100,000. How many years of useful life should be estimated for the reactor if 12 per cent of the total annual expenses for the plant are due to the cost for reactor depreciation? The straight-line method for determining depreciation should be used.

2. A company has been selling a soap containing 30 per cent by weight water at a price of $10 per 100 lb f.o.b. (i.e., freight on board, which means the laundry pays the freight charges). The company offers an equally effective soap containing only 5 per cent water. The water content is of no importance to the laundry, and it is willing to accept the soap containing 5 per cent water if the delivered costs are equivalent. If the freight rate is 70 cents per 100 lb, how much should the company charge the laundry per 100 lb f.o.b. for the soap containing 5 per cent water?

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* In Chap. 7 (Cost Estimation), Table 15 presents a compilation of factors that can be used for estimating the costs of individual components in the total product cost.

3. A rough rule of thumb for the chemical industry is that $1 of annual sales requires $1 of fixed-capital investment. In a chemical processing plant where this rule applies, the total capital investment is $2,500,000 and the working capital is 20 per cent of the total capital investment. The annual total product cost amounts to $1,500,000. If the national and regional income-tax rates on gross earnings total 52 per cent, determine the following:

(*a*) Per cent of total capital investment returned annually as gross earnings.

(*b*) Per cent of total capital investment returned annually as net profit.

4. A chemical processing unit has a capacity for producing 1 million lb of a product per year. After the unit has been put into operation, it is found that only 500,000 lb of the product can be disposed of per year. An analysis of the existing situation shows that all fixed and other invariant charges which must be paid whether or not the unit is operating amount to 35 per cent of the total product cost when operating at full capacity. Raw-material costs and other production costs that are directly proportional to the quantity of production (i.e., constant per pound of product at any production rate) amount to 40 per cent of the total product cost at full capacity. The remaining 25 per cent of the total product cost is for variable overhead and miscellaneous expenses, and the analysis indicates that these costs are directly proportional to the production rate during operation raised to the 1.5 power. What will be the per cent change in total cost per pound of product if the unit is switched from the 1-million-lb-per-year rate to a time and rate schedule which will produce 500,000 lb of product per year at the least total cost? All costs referred to above are on a per pound basis.

5. The initial installed cost for a new piece of equipment is $10,000, and its scrap value at the end of its useful life is estimated to be $2000. The useful life is estimated to be 10 years. After the equipment has been in use for 4 years, it is sold for $7000. The company which originally owned the equipment employs the straight-line method for determining depreciation costs. If the company had used an alternative method for determining depreciation costs, the asset (or book) value for the piece of equipment at the end of 4 years would have been $5240. The total income-tax rate for the company is 52 per cent of all gross earnings. Capital-gains taxes amount to 25 per cent of the gain. How much net saving after taxes would the company have achieved by using the alternative (in this case, reducing-balance) depreciation method instead of the straight-line depreciation method?

6. The total capital investment for a proposed chemical plant is estimated to be $1 million, and it will produce $1,500,000 worth of goods per year. It will be necessary to do a considerable amount of research and development work on the project before the final plant can be constructed, and management wishes to estimate the permissible research and development costs. It has been decided that the net profits from the plant should be sufficient to pay off the total capital investment plus all research and development costs in 7 years. A return after taxes of at least 12 per cent of sales must be obtained, and 50 per cent of the research and development cost is tax-free (i.e., income-tax rate for the company is 50 per cent of the gross earnings). Under these conditions, what is the total amount the company can afford to pay for research and development? See *Chem. Eng.*, **62**(1):130 (1955).

CHAPTER 3

INTEREST AND INVESTMENT COSTS

A considerable amount of confusion exists among engineers over the role of interest in determining costs for a manufacturing plant. The confusion is caused by the attempt to apply the classical economist's definition of interest. According to the classical definition, interest is the money returned to the owners of capital for use of their capital. This would mean that any profit obtained through the use of capital could be considered as interest. Modern economists seldom adhere to the classical definition. Instead, they prefer to substitute the term *return on capital* or *return on investment* for the classical *interest.*

Engineers define interest as the *compensation paid for the use of borrowed capital.* This definition permits distinction between profit and interest. The rate at which interest will be paid is usually fixed at the time the capital is borrowed, and a guarantee is made to return the capital at some set time.

TYPES OF INTEREST

Simple Interest. In economic terminology, the amount of capital on which interest is paid is designated as the *principal*, and *rate of interest* is defined as the amount of interest earned by a unit of principal in a unit of time. The time unit is usually taken as 1 year. For example, if \$100 were the compensation demanded for giving someone the use of \$1000 for a period of 1 year, the principal would be \$1000, and the rate of interest would be $^{100}/_{1000} = 0.1$, or 10 per cent per year.

The simplest form of interest requires compensation payment at a constant interest rate based only on the original principal. Thus, if \$1000 is loaned for a total time of 4 years at a constant interest rate of 10 per cent per year, the simple interest earned would be

$$\$1000 \times 0.1 \times 4 = \$400$$

If P represents the principal, n the number of time units or interest periods, and i the interest rate based on the length of one interest period, the amount of simple interest I during n interest periods is

$$I = Pin \tag{1}$$

The principal must be repaid eventually; therefore, the entire amount S of principal plus simple interest due after n interest periods is

$$S = P + I = P(1 + in) \tag{2}$$

Ordinary and Exact Simple Interest. The time unit used to determine the number of interest periods is usually 1 year, and the interest rate is expressed on a yearly basis. When an interest period of less than 1 year is involved, the *ordinary* way to determine simple interest is to assume the year consists of twelve 30-day months, or 360 days. The *exact* method accounts for the fact that there are 365 days in a normal year. Thus, if the interest rate is expressed on the regular yearly basis and d represents the number of days in an interest period, the following relationships apply:

$$\textit{Ordinary simple interest} = Pi\frac{d}{360} \tag{3}$$

$$\textit{Exact simple interest} = Pi\frac{d}{365} \tag{4}$$

Ordinary interest is commonly accepted in business practices unless there is a particular reason to use the exact value.

Compound Interest. In the payment of simple interest, it makes no difference whether the interest is paid at the end of each time unit or after any number of time units. The same total amount of money is paid during a given length of time, no matter which method is used. Under these conditions, there is no incentive to pay the interest until the end of the total loan period.

Interest, like all negotiable capital, has a time value. If the interest were paid at the end of each time unit, the receiver could put this money to use for earning additional profits. *Compound interest* takes this factor into account by stipulating that interest is due regularly at the end of each interest period. If payment is not made, the amount due is added to the principal, and interest is charged on this converted principal during the following time unit. Thus, an initial loan of \$1000 at an annual interest rate of 10 per cent would require payment of \$100 as interest at the end of the first year. If this payment were not made, the interest for the second year would be (\$1000 + \$100)(0.10) = \$110, and the total *compound amount* due after 2 years would be \$1000 + \$100 + \$110 = \$1210.

The compound amount due after any number of interest periods can be determined as follows:

Period	Principal at start of period	Interest earned during period (i = interest rate based on length of one period)	Compound amount S at end of period
1	P	Pi	$P + Pi = P(1 + i)$
2	$P(1 + i)$	$P(1 + i)(i)$	$P(1 + i) + P(1 + i)(i) = P(1 + i)^2$
3	$P(1 + i)^2$	$P(1 + i)^2(i)$	$P(1 + i)^2 + P(1 + i)^2(i) = P(1 + i)^3$
n	$P(1 + i)^{n-1}$	$P(1 + i)^{n-1}(i)$	$P(1 + i)^n$

Therefore, the total amount of principal plus compounded interest due after n interest periods is

$$S = P(1 + i)^n \tag{5}$$

The term $(1 + i)^n$ is commonly referred to as the *compound-interest factor*. Values for this factor at various interest rates and numbers of interest periods are given in Table 1.

Figure 3-1 shows a comparison between the total amount due at different times for the cases where simple interest and compound interest are used.

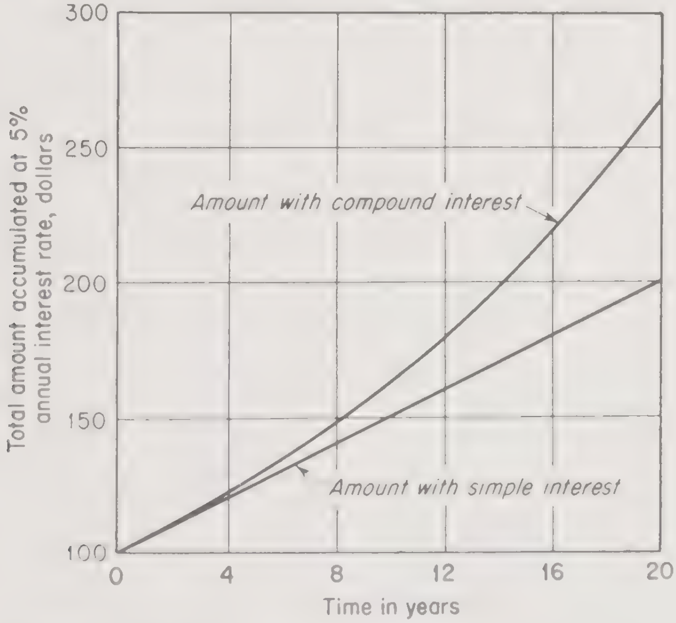

FIG. 3-1. Comparison between total amounts accumulated with simple interest and compound interest.

TABLE 1. COMPOUND-INTEREST FACTOR $(1 + i)^n$ AT VARIOUS VALUES OF i AND n

Per cent interest = $(i)(100)$

Number of interest periods, n	Value of $(1 + i)^n$ at indicated per cent interest													
	1%	2%	3%	4%	5%	6%	7%	8%	10%	12%	14%	16%	18%	20%
1	1.0100	1.0200	1.0300	1.0400	1.0500	1.0600	1.0700	1.0800	1.1000	1.1200	1.1400	1.1600	1.1800	1.2000
2	1.0201	1.0404	1.0609	1.0816	1.1025	1.1236	1.1449	1.1664	1.2100	1.2544	1.2996	1.3456	1.3924	1.4400
3	1.0303	1.0612	1.0927	1.1249	1.1576	1.1910	1.2250	1.2597	1.3310	1.4049	1.4815	1.5609	1.6430	1.7280
4	1.0406	1.0824	1.1255	1.1699	1.2155	1.2625	1.3108	1.3605	1.4641	1.5735	1.6890	1.8106	1.9388	2.0736
5	1.0510	1.1041	1.1593	1.2167	1.2763	1.3382	1.4026	1.4693	1.6105	1.7623	1.9254	2.1003	2.2878	2.4883
6	1.0615	1.1262	1.1941	1.2653	1.3401	1.4185	1.5007	1.5869	1.7716	1.9738	2.1950	2.4364	2.6996	2.9860
7	1.0721	1.1487	1.2299	1.3159	1.4071	1.5036	1.6058	1.7138	1.9487	2.2107	2.5023	2.8262	3.1855	3.5832
8	1.0829	1.1717	1.2668	1.3686	1.4775	1.5938	1.7182	1.8509	2.1436	2.4760	2.8592	3.2784	3.7589	4.2998
9	1.0937	1.1951	1.3048	1.4233	1.5513	1.6895	1.8385	1.9990	2.3579	2.7731	3.2520	3.8030	4.4355	5.1598
10	1.1046	1.2190	1.3439	1.4802	1.6289	1.7908	1.9672	2.1589	2.5937	3.1058	3.7072	4.4114	5.2338	6.1917
11	1.1157	1.2434	1.3842	1.5395	1.7103	1.8983	2.1049	2.3316	2.8531	3.4785	4.2262	5.1173	6.1759	7.4301
12	1.1268	1.2682	1.4258	1.6010	1.7959	2.0122	2.2522	2.5182	3.1384	3.8960	4.8179	5.9360	7.2876	8.9161
13	1.1381	1.2936	1.4685	1.6651	1.8856	2.1329	2.4098	2.7196	3.4523	4.3635	5.4924	6.8858	8.5994	10.699
14	1.1495	1.3195	1.5126	1.7317	1.9799	2.2609	2.5785	2.9372	3.7975	4.8871	6.2614	7.9875	10.147	12.839
15	1.1610	1.3459	1.5580	1.8009	2.0789	2.3966	2.7590	3.1722	4.1772	5.4736	7.1380	9.2655	11.974	15.407
16	1.1726	1.3728	1.6047	1.8730	2.1829	2.5404	2.9522	3.4259	4.5950	6.1304	8.1373	10.748	14.129	18.488
17	1.1843	1.4002	1.6528	1.9479	2.2920	2.6928	3.1588	3.7000	5.0545	6.8660	9.2765	12.468	16.672	22.186
18	1.1961	1.4282	1.7024	2.0258	2.4066	2.8543	3.3799	3.9960	5.5599	7.6900	10.575	14.462	19.673	26.623
19	1.2081	1.4568	1.7535	2.1068	2.5270	3.0256	3.6165	4.3157	6.1159	8.6128	12.056	16.777	23.214	31.948
20	1.2202	1.4859	1.8061	2.1911	2.6533	3.2071	3.8697	4.6610	6.7275	9.6463	13.744	19.461	27.393	38.338
21	1.2324	1.5157	1.8603	2.2788	2.7860	3.3996	4.1406	5.0338	7.4003	10.804	15.668	22.574	32.324	46.005
22	1.2447	1.5460	1.9161	2.3699	2.9253	3.6035	4.4304	5.4365	8.1403	12.100	17.861	26.186	38.142	55.206
23	1.2572	1.5769	1.9736	2.4647	3.0715	3.8197	4.7405	5.8715	8.9543	13.552	20.362	30.376	45.008	66.247
24	1.2697	1.6084	2.0328	2.5633	3.2251	4.0489	5.0724	6.3412	9.8497	15.179	23.212	35.236	53.109	79.497
25	1.2824	1.6406	2.0938	2.6658	3.3864	4.2919	5.4274	6.8485	10.835	17.000	26.462	40.874	62.669	95.396
30	1.3478	1.8114	2.4273	3.2434	4.3219	5.7435	7.6123	10.063	17.449	29.960	50.950	87.044	143.37	237.38
35	1.4166	1.9999	2.8139	3.9461	5.5160	7.6861	10.677	14.785	28.102	52.800	98.101	180.31	328.00	590.67
40	1.4889	2.2080	3.2620	4.8010	7.0400	10.286	14.974	21.725	45.259	93.051	188.88	378.72	750.38	1469.8
45	1.5648	2.4379	3.7816	5.8412	8.9850	13.765	21.002	31.920	72.891	163.99	363.68	795.44	1716.7	3657.2
50	1.6446	2.6916	4.3839	7.1067	11.467	18.420	29.457	46.902	117.39	289.00	700.24	1670.7	3927.3	9100.4

NOMINAL AND EFFECTIVE INTEREST RATES

In common industrial practice, the length of an interest period is assumed to be 1 year and the fixed interest rate i is based on 1 year. However, there are cases where other time units are employed. Even though the actual interest period is not 1 year, the interest rate is often expressed on an annual basis. Consider an example in which the interest rate is 3 per cent per period and the interest is compounded at half-year periods. A rate of this type would be referred to as "6 per cent compounded semiannually." Interest rates stated in this form are known as *nominal interest rates*. The actual annual return on the principal would not be exactly 6 per cent, but would be somewhat larger because of the compounding effect at the end of the semiannual period.

It is desirable to express the exact interest rate based on the original principal and the convenient time unit of 1 year. A rate of this type is known as the *effective interest rate*. The only time that nominal and effective interest rates are equal is when the interest is compounded annually.

If nominal interest rates are quoted, it is possible to determine the effective interest rate by proceeding from Eq. (5).

$$S = P(1 + i)^n \tag{5}$$

In this equation, S represents the total amount of principal plus interest due after n periods at the periodic interest rate i. Let j be the nominal interest rate under conditions where there are m conversions or interest periods per year. Then, the interest rate based on the length of one interest period is j/m, and the amount S after 1 year is

$$S_{\text{after 1 year}} = P\left(1 + \frac{j}{m}\right)^m \tag{6}$$

Designating the effective interest rate as i_e, the amount S after 1 year can be expressed in an alternative form as

$$S_{\text{after 1 year}} = P(1 + i_e) \tag{7}$$

By equating Eqs. (6) and (7), the following equation can be obtained for the effective interest rate in terms of the nominal interest rate and the number of periods per year:

$$i_e = \left(1 + \frac{j}{m}\right)^m - 1 \tag{8}$$

Example 1. Applications of Different Types of Interest. It is desired to borrow \$1000 to meet a financial obligation. This money can be borrowed from a loan agency at a monthly interest rate of 2 per cent. Determine the following:

a. The total amount of principal plus simple interest due after 2 years if no intermediate payments are made.

(*b*) The total amount of principal plus compounded interest due after 2 years if no intermediate payments are made.

(*c*) The nominal interest rate when the interest is compounded monthly.

(*d*) The effective interest rate when the interest is compounded monthly.

Solution

(*a*) Length of one interest period = 1 month
Number of interest periods in 2 years = 24
For simple interest, the total amount due after n periods at periodic interest rate i is

$$S = P(1 + in) \tag{2}$$

P = initial principal = \$1000
i = 0.02 on a monthly basis
n = 24 interest periods in 2 years

$$S = \$1000(1 + 0.02 \times 24) = \$1480$$

(*b*) For compound interest, the total amount due after n periods at periodic interest rate i is

$$S = P(1 + i)^n \tag{5}$$

$$S = \$1000(1 + 0.02)^{24} = \$1608$$

(*c*) Nominal interest rate = 2 × 12 = 24% per year compounded monthly

(*d*) Number of interest periods per year = m = 12
Nominal interest rate = j = 0.24

$$\text{Effective interest rate} = \left(1 + \frac{j}{m}\right)^m - 1 \tag{8}$$

$$\text{Effective interest rate} = \left(1 + \frac{0.24}{12}\right)^{12} - 1 = 0.268 = 26.8\%$$

PRESENT VALUE AND DISCOUNT

It is often necessary to determine the amount of money which must be available at the present time in order to have a certain amount accumulated at some time in the future. Because the element of time is involved, interest must be taken into consideration. The *present value* of a future amount is the present principal which must be deposited at a given interest rate to yield the desired amount at some future date.

In Eq. (5), S represents the amount available after n interest periods if the initial principal is P and the compound interest rate is i. Therefore, the present value can be determined by merely rearranging Eq. (5).

$$\text{Present value} = P = S\frac{1}{(1 + i)^n} \tag{9}$$

The factor $1/(1 + i)^n$ is commonly referred to as the *present-value factor*.

Some types of capital are in the form of bonds having an indicated value at a future date. In business terminology, the difference between the indicated future value and the present value is known as the *discount*.

Example 2. Determination of Present Value and Discount. A bond has a maturity value of \$1000 and is paying compound interest at an annual rate of 3 per cent. Determine the following at a time 4 years before the bond reaches its maturity value:

(*a*) Present value.

(*b*) Discount.

(*c*) Compound rate of interest which will be received by a purchaser if he obtained the bond for \$700.

Solution

(*a*) By Eq. (9), present value $= \dfrac{S}{(1+i)^n} = \dfrac{\$1000}{(1+0.03)^4} = \$888$

(*b*) Discount = future value − present value = \$1000 − \$888 = \$112

(*c*) Principal $= \$700 = \dfrac{S}{(1+i)^n} = \dfrac{\$1000}{(1+i)^4}$

$$i = (1000/700)^{1/4} - 1 = 0.0935 = 9.35\%$$

ANNUITIES

An *annuity* is a series of equal payments occurring at equal time intervals. Payments of this type can be used to pay off a debt, accumulate a desired amount of capital, or receive a lump sum of due capital in periodic installments as in some life-insurance plans. Engineers often encounter annuities in depreciation calculations, where the decrease in value of equipment with time is accounted for by an annuity plan.

The common type of annuity involves payments which occur *at the end of each interest period*. This is known as an *ordinary annuity*.* Interest is paid on all accumulated amounts, and the interest is compounded each payment period. An *annuity term* is the time from the beginning of the first payment period to the end of the last payment period. The *amount of an annuity* is the sum of all the payments plus interest if allowed to accumulate at a definite rate of interest from the time of initial payment to the end of the annuity term.

Relation between Amount of Ordinary Annuity and the Periodic Payments. Let R represent the uniform periodic payment made during n periods in an ordinary annuity. The interest rate based on the payment period is i, and S is the amount of the annuity. The first payment of R is made at the end of the first period and will bear interest for $n - 1$

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* For a discussion of the relative merits of ordinary annuities and annuities due as applied in chemical engineering calculations, see *Chem. Eng.*, **62**(12):350 (1955).

periods. Thus, at the end of the annuity term, this first payment will have accumulated to an amount of $R(1+i)^{n-1}$. The second payment of R is made at the end of the second period and will bear interest for $n - 2$ periods giving an accumulated amount of $R(1+i)^{n-2}$. Similarly, each periodic payment will give an additional accumulated amount until the last payment of R is made at the end of the annuity term.

By definition, the amount of the annuity is the sum of all the accumulated amounts from each payment; therefore,

$$S = R(1+i)^{n-1} + R(1+i)^{n-2} + R(1+i)^{n-3} + \cdots + R(1+i) + R \qquad (10)$$

To simplify Eq. (10), multiply each side by $(1 + i)$ and subtract Eq. (10) from the result. This gives

$$Si = R(1+i)^n - R \qquad (11)$$

or

$$S = R\frac{(1+i)^n - 1}{i} \qquad (12)$$

The term $\frac{(1+i)^n - 1}{i}$ is commonly designated as the *series-amount factor* or the *future-worth factor*.

Present Value of an Annuity. The *present value of an annuity* is defined as the principal which would have to be invested at the present time at compound interest rate i to yield a total amount at the end of the annuity term equal to the amount of the annuity. Let P represent the present value of an ordinary annuity. Combining Eq. (5) with Eq. (12) gives

$$P = R\frac{(1+i)^n - 1}{i(1+i)^n} \qquad (13)$$

The expression $\frac{(1+i)^n - 1}{i(1+i)^n}$ is sometimes referred to as the *series present-value factor.*

Example 3. Application of Annuities in Determining Amount of Depreciation. A piece of equipment has an initial installed value of $12,000. It is estimated that its useful life period will be 10 years and its scrap value at the end of the useful life will be $2000. The depreciation will be charged as a cost by making equal charges each year, the first payment being made at the end of the first year. The depreciation fund will be accumulated at an annual interest rate of 6 per cent. At the end of the life period, enough money must have been accumulated to account for the decrease in equipment value. Determine the yearly cost due to depreciation under these conditions.

NOTE: *This method for determining depreciation is based on an ordinary annuity and is known as the sinking-fund method.*

Solution

This problem is a typical case of an ordinary annuity. Over a period of 10 years, equal payments must be made each year at an interest rate of 6 per cent. After 10 years, the amount of the annuity must be equal to the total amount of depreciation.

Amount of annuity = S
Total amount of depreciation = \$12,000 − \$2000 = \$10,000
Equal payments per year = R = yearly cost due to depreciation
Number of payments = $n = 10$
Annual interest rate = $i = 0.06$
From Eq. (12)

$$R = S\frac{i}{(1+i)^n - 1} = \$10{,}000\,\frac{0.06}{(1.06)^{10} - 1} = \$759 \text{ per year}$$

Yearly cost due to depreciation = \$759

Special Types of Annuities. One special form of an annuity requires that payments be made at the beginning of each period instead of at the end of each period. This is known as an *annuity due*. An annuity in which the first payment is due after a definite number of years is called a *deferred annuity*. Determination of the periodic payments, amount of annuity, or present value for these two types of annuities can be accomplished by methods analogous to those used in the case of ordinary annuities.*

Perpetuities and Capitalized Costs

A *perpetuity* is an annuity in which the periodic payments continue indefinitely. This type of annuity is of particular interest to engineers, for in some cases they may desire to determine a total cost for a piece of equipment or other asset under conditions which permit the asset to be replaced perpetually.

Consider the example in which the original cost of a certain piece of equipment is \$12,000. The useful-life period is 10 years, and the scrap value at the end of the useful life is \$2000. The engineer reasons that this piece of equipment, or its replacement, will be in use for an indefinitely long period of time, and it will be necessary to supply \$10,000 every 10 years in order to replace the equipment. He therefore wishes to provide a fund of sufficient size so that it will earn enough interest to pay for the periodic replacement. If the annual interest rate is 6 per cent, this fund would need to be \$12,650. At 6 per cent interest compounded annually, the fund would amount to $(\$12{,}650)(1 + 0.06)^{10} = \$22{,}650$ after 10 years. Thus, at the end of 10 years, the equipment can be replaced for \$10,000 and \$12,650 will remain in the fund. This cycle could now be repeated indefinitely. If the equipment is to perpetuate itself, the theoretical amount of total capital necessary at the start would be \$12,000 for the equipment plus \$12,650 for the replacement fund. The total capital determined in this manner is called the *capitalized cost*. Engineers use capitalized costs principally for comparing alternative choices.*

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* For further information, see B. M. Woods and E. P. DeGarmo, "Introduction to Engineering Economy," 2d ed., The Macmillan Company, New York, 1953.

In a perpetuity, such as in the preceding example, the amount required for the replacement must be earned as compounded interest over a given length of time. Let P be the amount of present principal (i.e., the present value) which can accumulate to an amount S during n interest periods at periodic interest rate i. Then, by Eq. (5),

$$S = P(1 + i)^n \tag{5}$$

If perpetuation is to occur, the amount S accumulated after n periods minus the cost for the replacement must equal the present value P. Therefore, letting C_R represent the replacement cost,

$$P = S - C_R \tag{14}$$

Combining Eqs. (5) and (14),

$$P = \frac{C_R}{(1 + i)^n - 1} \tag{15}$$

The capitalized cost is defined as the original cost of the equipment plus the present value of the renewable perpetuity. Designating K as the capitalized cost and C_V as the original cost of the equipment,

$$K = C_V + \frac{C_R}{(1 + i)^n - 1} \tag{16}$$

Example 4. Determination of Capitalized Cost. A new piece of completely installed equipment costs \$12,000 and will have a scrap value of \$2000 at the end of its useful life. If the useful-life period is 10 years and the interest is compounded at 6 per cent per year, what is the capitalized cost of the equipment?

Solution

The cost for replacement of the equipment at the end of its useful life (assuming costs unchanged) = \$12,000 − \$2000 = \$10,000.

By Eq. (16)

$$\text{Capitalized cost} = C_V + \frac{C_R}{(1 + i)^n - 1}$$

where $C_V = \$12,000$
$C_R = \$10,000$
$i = 0.06$
$n = 10$

$$\text{Capitalized cost} = \$12,000 + \frac{\$10,000}{(1 + 0.06)^{10} - 1}$$

$$= \$12,000 + \$12,650 = \$24,650$$

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* For further discussion of capitalized costs used in engineering, see Chap 6 and F. C. Jelen, *Chem. Eng.*, **61**(2):199 (1954); **61**(6):407 (1954); **62**(8):181 (1955); **62**(12): 183, 350 (1955); **63**(5):165 (1956); **63**(6):247 (1956); and *Chem. Eng. Prog.*, **52**:413 (1956).

Example 5. Comparison of Alternative Investments Using Capitalized Costs. A reactor, which will contain corrosive liquids, has been designed. If the reactor is made of mild steel, the initial installed cost will be \$5000, and the useful-life period will be 3 years. Since stainless steel is highly resistant to the corrosive action of the liquids, stainless steel, as the material of construction, has been proposed as an alternative to mild steel. The stainless-steel reactor would have an initial installed cost of \$15,000. The scrap value at the end of the useful life would be zero for either type of reactor, and both could be replaced at a cost equal to the original price. On the basis of equal capitalized costs for both types of reactors, what should be the useful-life period for the stainless-steel reactor if money is worth 4 per cent compounded annually?

Solution

By Eq. (16), the capitalized cost for the mild-steel reactor is

$$K = C_V + \frac{C_R}{(1+i)^n - 1} = \$5000 + \frac{\$5000}{(1+0.04)^3 - 1}$$

$$K = \$5000 + \$40{,}030 = \$45{,}030$$

Therefore, the capitalized cost for the stainless-steel reactor must also be \$45,030. For the stainless-steel reactor

$$\$45{,}030 = C_V + \frac{C_R}{(1+i)^n - 1} = \$15{,}000 + \frac{\$15{,}000}{(1+0.04)^n - 1}$$

Solving algebraically for n,

$$n = 10.4 \text{ years}$$

Thus, the useful-life period of the stainless-steel reactor should be 10.4 years for the two types of reactors to have equal capitalized costs. If the stainless-steel reactor would have a useful life of more than 10.4 years, it would be the recommended choice, while the mild-steel reactor would be recommended if the useful life using stainless steel were less than 10.4 years.

COSTS DUE TO INTEREST ON INVESTMENT

Money, or any other negotiable type of capital, has a time value. When a business concern invests money, it expects to receive a return during the time the money is tied up in the investment. The amount of return demanded usually depends on the degree of risk that the entire investment might be lost.

One of the duties of a design engineer is to determine the net return or profit which can be obtained by making an investment. It is necessary, therefore, to find the total cost involved. Too often, the engineer fails to recognize the time value of money and neglects the effects of interest on cost. According to the modern definition of interest, the cost due to time value of an investment should be included as interest if any portion of the total capital investment comes from outside sources.

Borrowed Capital versus Owned Capital. The question sometimes arises as to whether interest on owned capital can be charged as a true cost. The modern definition of interest permits a definite answer of "no" to this question. Court decisions and income-tax regulations verify this answer.

Interest Effects in a Small Business. In small business establishments, it is usually quite easy to determine the exact source of all capital. Therefore, the interest costs can be obtained with little difficulty. For example, suppose that a young chemical engineer has \$20,000 and he decides to set up a small plant for producing antifreeze from available raw materials. If his working capital plus fixed-capital investment is \$20,000, he finds he can invest his own money and make a total yearly profit of \$8000 before income taxes. In this case, interest obviously could not be included as a cost. If it had been necessary to borrow the \$20,000 at an annual interest rate of 6 per cent, interest would have been a cost, and the total profit would have been \$8000 − (0.06)(\$20,000) = \$6800 per year.

Interest Effects in a Large Business. In large business establishments, new capital may come from issue of stocks and bonds, borrowing from banks or insurance companies, funds set aside for replacement of worn-out or obsolete equipment, profits received but not distributed to the stockholders, and other sources. Therefore, it is often difficult to designate the exact source of new capital, and the particular basis used for determining interest costs should be indicated when the results of a cost analysis are reported.

An approximate breakdown showing the various sources of new capital for large corporations is presented in Table 2.

TABLE 2. SOURCE OF NEW CAPITAL FOR CORPORATIONS *

Source of capital	Approximate amount of total new capital, %
External financing (loans from banks or other concerns, issue of stocks and bonds)	25
Profits earned but not distributed to stockholders as dividends	32
Depreciation funds set aside	24
Miscellaneous	19

* National Industrial Conference Board, "Profits in Perspective," p. 25, May 21–22, 1953.

Source of Capital

One source of new capital is outside loans. Interest on such loans is usually at a fixed rate, and the annual cost can be determined directly.

New capital may also be obtained from the issue of bonds, preferred stock, or common stock. Interest on bonds and preferred-stock dividends must be paid at fixed rates. A relatively low interest rate is paid on bonds because the bondholder has first claim on earnings, while higher rates are paid on preferred stock because the holder has a greater chance to lose his entire investment. The holder of common stock accepts all the risks involved in owning a business. The return on common stock, therefore, is not at a fixed rate but varies depending on the success of the company which issued the stock. To compensate for this greater risk, the return on common stock may be much higher than that on bonds or preferred stock.

Income-tax Effects. The effect of high income-tax rates on the cost of capital is very important. In determining income taxes, interest on loans and bonds can be considered as a cost, while the return on both preferred and common stock cannot be included as a cost. Since corporate income taxes can amount to more than half of the gross earnings, the source of new capital may have a considerable influence on the net profits.

If the annual income-tax rate for a company is 52 per cent, every dollar spent for interest on loans or bonds would have a true cost after taxes of only 48 cents. Thus, after income taxes are taken into consideration, a bond issued at an annual interest rate of 3 per cent would actually have an interest rate of only $3 \times {}^{48}/_{100} = 1.44$ per cent. On the other hand, the dividends on preferred stock must be paid from net profits after taxes. If preferred stock has an annual dividend rate of 4 per cent, the equivalent rate before taxes would be $4 \times {}^{100}/_{48} = 8.33$ per cent.

TABLE 3. TYPICAL COSTS FOR EXTERNALLY FINANCED CAPITAL

Income tax rate = 52% of (total income − total pretax cost)

Source of capital	Indicated interest or dividend rate, %/year	Actual interest or dividend rate before taxes, %/year	Actual interest or dividend rate after taxes, %/year
Bonds	3	3	1.44
Bank or other loans	4	4	1.92
Preferred stock	4	8.33	4
Common stock	0	16.66	8

Despite the fact that it may be cheaper to use borrowed capital in place of other types of capital, it is unrealistic to finance each new venture by using borrowed capital. Every corporation needs to maintain a balanced capital structure and is therefore hesitant about placing itself under a heavy burden of debt.

A comparison of interest or dividend rates for different types of externally financed capital is presented in Table 3.

Methods for Including Cost of Capital in Economic Analyses

The cost of new capital obtained from bonds, loans, or preferred stock can be determined directly from the stated interest or dividend rate, adjusted for income taxes. However, the cost of new capital obtained from the issue of common stock is not so obvious, and some basis must be set for determining this cost. Probably the fairest basis is to consider the viewpoint of existing holders of common stock. If new common stock is issued, its per cent return should be at least as much as that obtained from the old common stock; otherwise, the existing stockholders would receive a lower return after the issue of the new stock. Therefore, from the viewpoint of the existing stockholders, the cost of new common stock is the present rate of common-stock earnings.*

A major source of new capital is from internal capital, including, primarily, undistributed profits and depreciation funds. Since this definitely is owned capital, it is not necessary to consider interest as a cost. However, some concerns prefer to assign a cost to this type of capital, particularly if comparisons of alternative investments are to be made. The reasoning here is that the owned capital could be loaned out or put into other ventures to give a definite return.

Two methods are commonly used for determining the cost of owned capital. In the first method, the capital is charged at a low interest rate on the assumption that it could be used to pay off funded debts or invest in risk-free loans. The second method requires interest to be paid on the owned capital at a rate equal to the present return on all the company's capital.

Design-Engineering Practice for Interest and Investment Costs. Many alternative methods are used by engineers when determining interest costs in an economic analysis of a design project. In preliminary designs, one of the following two methods is usually employed:

1. No interest costs are included. This assumes that all the necessary capital comes from owned capital, and any comparisons to alternative investments must be on the same basis.

2. Interest is charged on the total capital investment at a set interest rate. Low rates, equivalent to those charged for bank loans or bonds, are

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* For further discussion on this matter, see W. Buell, *Chem. Eng.*, **61**(5):183 (1954).

usually employed. Under these conditions, the total profit represents the increase over the return that would be obtained if the company could invest the same amount of money in an outside loan at the given interest rate.

As the design proceeds to the final stages, the actual source of the new capital should be considered in detail, and more refined methods for determining interest costs can be used.

There is some question as to whether interest costs should be based on the initial investment or on the average investment over the life of the project. Although this is a debatable point, the accepted design practice is to base the interest costs on the initial investment.

Because of the different methods used for treating interest as a cost, a definite statement should be made concerning the particular method employed in any given economic analysis. Interest costs become especially important when making comparisons among alternative investments. These comparisons, as well as the over-all cost picture, are simplified if the role of interest in the economic analysis is clearly defined.

NOMENCLATURE FOR CHAP. 3

C_R = cost for replacement of equipment or other asset, dollars
C_V = original cost of equipment or other asset, dollars
d = number of days in an interest period, days
i = interest rate based on the length of one interest period, per cent/100
i_e = effective interest rate—exact interest rate based on an interest period of 1 year, per cent/100
I = total amount of interest during n interest periods, dollars
j = nominal interest rate—approximate interest rate based on an interest period of 1 year, per cent/100
K = capitalized cost, dollars
m = number of interest periods per year
n = number of time units or interest periods
P = principal or present value of capital on which interest is paid, dollars
R = uniform periodic payments made during n periods in an ordinary annuity, \$/period.
S = amount of principal or present value plus interest due after n interest periods, dollars

PROBLEMS

1. It is desired to have \$9000 available 12 years from now. If \$5000 is available for investment at the present time, what annual rate of compound interest on the investment would be necessary to give the desired amount?

2. What will be the total amount available 10 years from now if \$2000 is deposited at the present time with nominal interest at the rate of 6 per cent compounded semiannually?

3. An original loan of \$2000 was made at 4 per cent simple interest per year for 4 years. At the end of this time, no interest had been paid and the loan was extended for 6 more years at a new, compound interest rate of 6 per cent per year. What is the total amount owed at the end of the 10 years if no intermediate payments are made?

4. A concern borrows $50,000 at an annual compound interest rate of 6 per cent. The concern wishes to pay off the debt in 5 years by making equal payments at the end of each year. How much will each payment have to be?

5. The original cost for a distillation tower is $24,000, and the useful life of the tower is estimated to be 8 years. The sinking-fund method for determining the rate of depreciation is used (see Example 3), and the annual interest rate for the depreciation fund is 4 per cent. If the scrap value of the distillation tower is $4000, determine the asset value (i.e., total book value of equipment) at the end of 5 years.

6. An annuity due is being used to accumulate money. Interest is compounded at an annual rate of 5 per cent, and $1000 is deposited at the beginning of each year. What will the total amount of the annuity due be after 5 years?

7. A heat exchanger has been designed for use in a chemical process. A standard type of heat exchanger with a negligible scrap value costs $1000 and will have a useful life of 6 years. Another proposed heat exchanger of equivalent design capacity costs $1700 but will have a useful life of 10 years and a scrap value of $200. Assuming a compound interest rate of 5 per cent per year, determine which heat exchanger is cheaper by comparing the capitalized costs.

8. A new storage tank can be purchased and installed for $10,000. This tank would last for 10 years. A worn-out storage tank of capacity equivalent to the new tank is available, and it has been proposed to repair the old tank instead of buying the new tank. If the tank were repaired, it would have a useful life of 3 years before the same type of repairs would be needed again. Neither tank has any scrap value. Money is worth 4 per cent compounded annually. On the basis of equal capitalized costs for the two tanks, how much can be spent for repairing the existing tank?

9. The total investment required for a new chemical plant is estimated at $2 million. Fifty per cent of the investment will be supplied from the company's own capital. Of the remaining investment, 50 per cent will come from a loan at an annual interest rate of 4 per cent and the other 50 per cent will come from an issue of preferred stock paying dividends at a stated rate of 4 per cent annually. The income-tax rate for the company is 47 per cent of pretax earnings. Under these conditions, how many dollars per year does the company actually lose (i.e., after taxes) by issuing preferred stock at 4 per cent dividends instead of bonds at an annual interest rate of 3 per cent?

10. It has been proposed that a company invest $1 million in a venture which will yield a gross income of $1 million per year. The total annual costs will be $800,000 per year including interest on the total investment at an annual rate of 6 per cent. In an alternative proposal, the company can invest a total of $600,000 and receive annual net earnings (before income taxes) of $220,000 from the venture. In this case, the net earnings were determined on the basis of no interest costs. The company has $1 million of its own which it wishes to invest, and it can always obtain a 4 per cent annual interest rate by loaning out the money. What would be the most profitable way for the company to invest its $1 million?

CHAPTER 4

TAXES AND INSURANCE

Expenses for taxes and insurance play an important part in determining the economic situation for any industrial process. Since modern taxes may amount to a major portion of a concern's earnings, it is essential for the design engineer to understand the basic principles and factors underlying taxation. Insurance costs ordinarily are only a small part of the total expenditure involved in an industrial operation; however, adequate insurance coverage is necessary before any operation can be carried out on a sound economic basis.

Taxes are levied to supply funds to meet the public needs of a government, while insurance is required for protection against certain types of emergencies or catastrophic occurrences. Insurance rates and tax rates can vary considerably for business concerns as compared to the rates for individual persons. The information presented in this chapter applies generally to large business establishments.

TYPES OF TAXES

Taxes may be classified into three types: (1) property taxes, (2) excise taxes, and (3) income taxes. These taxes may be levied by the Federal government, state governments, or local governments such as those connected with a county, city, or town.

Property Taxes. Local governments usually have jurisdiction over *property taxes*, which are commonly charged on a county basis. In addition to these, individual cities and towns may have special property taxes for industrial concerns located within the city limits.

Property taxes vary widely from one locality to another, but the average annual amount of these charges is 1 to 4 per cent of the assessed valuation. Taxes of this type are referred to as *direct* since they must be paid directly by the particular concern and cannot be passed on as such to the consumer.

Excise Taxes. *Excise taxes* are levied by Federal and state governments. Federal excise taxes include charges for import customs duties, transfer of stocks and bonds, and a large number of other similar items. Manufacturers' and retailers' excise taxes are levied by Federal and state governments on the sale of many products such as gasoline and alcoholic beverages. Taxes of this type are often referred to as *indirect* since they can be passed on to the consumer. Many business concerns must also pay excise taxes for the privilege of carrying on a business or manufacturing enterprise in their particular localities.

Income Taxes. In general, *income taxes* are based on gross earnings, which are defined as the difference between total income and total product cost. Revenue from income taxes is an important source of capital for both Federal and state governments. National and state laws are the basis for these levies, and the laws change from year to year. State income taxes vary from one state to another and are a function of the total income for individual concerns. Depending on the particular state and the existing laws, state income taxes may range from 0 to 5 per cent or more of gross earnings.

FEDERAL INCOME TAXES

The Federal government has set up an extremely complex system for determining income taxes for business establishments. New laws are added and old laws are changed each year, and it would be impossible to present all the rules and interpretations in a few pages.* Accordingly, this section will deal only with the basic pattern of Federal income-tax regulations and give the methods generally used for determining Federal income taxes. It should be emphasized strongly that the final determination of income-tax payments should be made with the aid of legal and accounting tax experts.

The corporate income-tax rate in the United States has varied widely during the past 50 years. During the period from 1913 to 1935 the tax rate based on gross earnings increased from 1 to 13.75 per cent. In 1938, the rate was increased to 19 per cent, and, during the Second World War, it was 40 per cent plus an excess-profits tax. In 1946, the standard income-tax rate for corporations was reduced to 38 per cent, but the rate was increased to 42 per cent in 1950 plus an excess-profits tax. During the Korean War, the rate was 52 per cent plus an excess-profits tax which could make an over-all tax rate of 70 per cent on gross earnings. In 1956, the corporation income-tax rate was 52 per cent. Table 1 shows the standard tax rates for corporations during the period 1929 to 1956.

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* A complete manual entitled *Federal Tax Regulations* giving the latest tax laws with interpretations and example cases is put out yearly through the *U.S. Code Congressional and Administrative News*, West Publishing Co., St. Paul, Minn., and Edward Thompson Co., Brooklyn, N.Y.

TABLE 1. NATIONAL TAXES ON CORPORATION PROFITS

Year	Regular tax rate, %	Effective limit with wartime excess-profits tax, %
United States:		
1929	11	
1930–1931	12	
1932–1935	13.75	
1936–1937	15	
1938–1939	19	
1940	24	
1941	31	
1942–1943	40	80
1944–1945	40	72
1946–1949	38	
1950	42	52
1951	50.75	68
1952–1953	52	70
1954	52	
1955	52	
1956	52	
Britain:		
1954	47.5	
Canada:		
1954	45	
Western Germany:		
1954	45	

The preceding figures indicate the wide variations in income-tax rate caused by national emergencies, the prevailing economic situation, and the desires of the lawmakers in power at any particular time. Figure 4-1 presents a graphical representation showing the changes in income-tax rates for a typical chemical company from 1943 to 1955.

Many industries have special tax exemptions because of the type of product, market, or service involved in their business, or because the government wishes to offer particular support and inducement to concerns producing essential materials. For example, in the high-tax year of 1951, the average tax rate for 10 major petroleum-processing plants was only 36.6 per cent of the gross income, but the average rate was 62 per cent for 27 major companies producing basic and intermediate chemicals.* Table 2 presents a comparison of income-tax rates at different times for various types of chemical industries.

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* Financial Records of 100 Chemical Process Companies, *Ind. Eng. Chem.*, **46**:1094 (1954).

Normal Tax. A so-called *normal tax* is levied by the Federal government on the gross earnings of corporations. This tax is at a rate set by the national lawmakers. In 1956, the normal tax in the United States was 30 per cent of gross earnings.

Surtax. In addition to the normal tax, corporations must pay a second Federal income tax on all gross earnings above a certain base limit. This additional tax is known as a *surtax*. The base limit was $25,000 per year in 1956, and the surtax on all earnings above this limit was at a rate of 22 per cent.

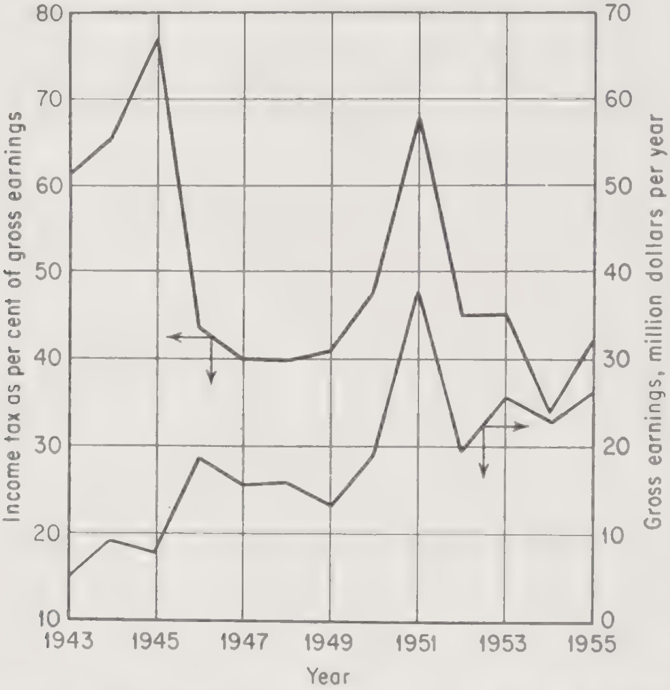

FIG. 4-1. Example of variation in income-tax rate with time for a chemical company. (*Based on annual reports by Chas. Pfizer and Company, Inc.*)

Excess-profits Tax. During times of national emergency, certain types of business concerns can realize an extremely high income. This is true in particular for concerns producing military necessities during wartime. An *excess-profits tax* is levied, therefore, to supply the national government with part of these profits.

The system for determining excess-profits taxes is extremely complex. In general, the amount of the tax is based on the normal past earnings of a concern or on the total capital investment. Special provisions are made for new corporations or for concerns which do not have a normal past history to use as a basis.

TABLE 2. FEDERAL INCOME-TAX RATES FOR VARIOUS TYPES OF INDUSTRIES *

Type and number of companies	Year	Average gross earnings per company, in thousands of dollars	Federal income tax, % of gross earnings
Chemical—basic- and intermediate-chemicals manufacture (27, 30 companies in 1954 and 1955)	1939	8,650	15.2
	1951	54,400	62.0
	1952	47,000	58.5
	1953	49,700	57.8
	1954	41,600	44.7
	1955	56,600	45.4
Chemical processes—application of chemical-engineering processes during manufacturing operation (24, 20 companies in 1954 and 1955)	1939	6,520	19.0
	1951	31,200	59.1
	1952	26,500	55.8
	1953	28,900	56.1
	1954	34,500	50.4
	1955	40,500	57.3
Drug and pharmaceutical—medicinal chemical and pharmaceuticals preparation and manufacture (11, 12 companies in 1954 and 1955)	1939	3,770	19.7
	1951	24,000	58.9
	1952	17,600	51.8
	1953	18,200	52.7
	1954	17,600	46.2
	1955	23,800	47.5
Extraction and mining—ore and mineral extraction (13, 12 companies in 1954 and 1955)	1939	1,860	15.5
	1951	13,200	51.0
	1952	11,700	43.2
	1953	13,200	45.0
	1954	14,900	39.2
	1955	17,500	39.7
Petroleum—oil and natural-gas production and refining (10, 11 companies in 1954 and 1955)	1939	28,500	14.8
	1951	237,000	36.6
	1952	206,000	28.6
	1953	225,000	30.2
	1954	212,000	26.3
	1955	253,000	28.5
Pulp and paper manufacture (7 companies)	1939	2,020	18.8
	1951	30,800	56.0
	1952	26,500	54.1
	1953	23,300	49.2
	1954	26,800	49.3
	1955	34,400	47.6
Rubber—rubber and rubber-products manufacture (4 companies)	1939	10,000	16.1
	1951	112,600	66.7
	1952	92,500	61.5
	1953	93,100	56.3
	1954	75,700	48.8
	1955	103,000	52.7
Synthetic fibers—rayon and other synthetic-fibers manufacture (4 companies)	1939	4,300	18.1
	1951	38,800	59.4
	1952	22,600	50.0
	1953	19,200	50.8
	1954	13,900	46.9
	1955	26,600	49.6

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* Based on Financial Records of 100 Chemical Process Companies, *Ind. Eng. Chem.*, **46**:1094 (1954); *Chem. Eng. News*, **34**:5641 (1956).

The excess-profits taxes are very unpopular with businessmen, and there is always considerable opposition to the levying of these taxes. Many articles have been written concerning the detrimental effects of excess-profits taxes and income taxes in general.*

Capital-gains Taxes. A *capital-gains tax* is levied on profits made from the sale of capital assets, such as land, buildings, or equipment. When the capital asset is sold after being held in possession for more than 6 months, the profit is known as a *long-term capital gain*. In 1956, the tax rate on long-term capital gains was 25 per cent.

Tax Returns. Income-tax returns may be reported on a cash basis or on an accrual basis. When the cash basis is used, only money actually received or paid out during the year is reported. With the accrual method, income and expenses are included as of the time they were incurred, even though final payment has not yet been made.

Returns may be based on a standard calendar year or on a fiscal year. Any date may be chosen as the end of the fiscal year, and it is usually advisable to choose a time when the work of assembly and determination of the tax will be the most convenient. The tax payment itself may be made in installments. In 1955, the payment could be in two equal installments with the first payment due on the fifteenth day of the third month after the end of the taxable year and the second payment due 3 months later. Tax payments may also be made on the basis of estimated income taxes for the current year.†

OTHER TAXES

The Federal Insurance Contribution Act levies a social security tax on most employers and also requires a certain percentage of employees' wages to be withheld. Special local assessments for tax purposes are often encountered, and concerns doing business in foreign countries must pay taxes based on the laws of the foreign countries involved.

The question sometimes arises in cost accounting whether certain service charges and license fees can be considered as taxes. If the charge can be regarded as part of a public duty to support government, it is legally correct to designate the charge as a tax. When the exaction is for a service and the amount charged is a reasonable fee for the service actually received, the cost cannot be considered as a tax. Fees for building permits, government inspections, formation of corporations, bridge and road tolls, and certain types of licenses cannot be charged as taxes because the primary purpose of these fees is to serve for control and regulation rather than to support government.

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* C. G. Kirkbride, *Chem. Eng. Progr.*, **48**:44 (1952); **50**:542 (1954).

† For an outline of regulations on pay-as-you-go income taxes, see *U.S. News and World Report*, July 8, 1955, p. 96.

If a corporation is organized by an individual for the purpose of avoiding high personal-income taxes, the organization is classed as a personal-holding company, and special tax rates apply. The amount of income tax which must be paid by a private business exceeds that required of an equivalent corporation at surprisingly small gross earnings. Consequently, a private business should make a periodic analysis of the advantages and disadvantages of becoming incorporated.

INSURANCE

The annual insurance cost for ordinary industrial concerns is approximately 1 per cent of the capital investment. Despite the fact that insurance costs may represent only a small fraction of total costs, it is necessary to consider insurance requirements carefully to make certain the economic operation of a plant is protected against emergencies or unforeseen developments.

The design engineer can aid in reducing insurance requirements if he understands the factors which must be considered in obtaining adequate insurance. In particular, the engineer should be aware of the different types of insurance available and the legal responsibilities of a concern with regard to accidents or other unpredictable emergencies.

Legal Responsibility

A concern can obtain insurance to protect itself against loss of property owing to any of a number of different causes. In case a property loss occurs and the loss is covered by insurance, payment will be made for the damage even though the loss was caused by the owner's negligence.

Protection against unforeseen emergencies, other than direct property loss, can also be obtained through insurance. For example, injuries to employees or persons near the danger area may occur due to a fire or explosion, and the concern involved should have insurance adequate to handle claims made in these cases. It is, of course, impossible to insure against every possible emergency, but it is necessary to consider the results of a potential occurrence, and the legal responsibility for various types of events should be understood. The payments required for settling a case in which legal responsibility has been proved may be much greater than any costs due to direct property damage.

An *assumed liability* is one which the concern accepts in the form of a written contract or statement, while a *legal liability* is always in effect whether or not it is stated in writing. Legal liabilities include civil responsibility for events occurring because of damage or injuries due to negligence. A stronger type of legal liability is known as *criminal liability*. This is involved in cases where gross negligence or reckless disregard for the life and property of others is claimed.

The design engineer should be familiar with the legal aspects of any laws or regulations governing the type of plant or process involved in a design. In case of an accident, failure to comply with the definite laws involved is a major factor in fixing legal responsibility. Compliance with all existing laws, however, is not a sufficient basis for disallowance of legal liability. Every known safety feature should be included and extraordinary care in the complete operation must be proved before a good case can be presented for disallowing legal liability.

Many contracts include *hold-harmless agreements* wherein the legal responsibility for an accident or other type of event is indicated as part of a written agreement. Any new lease or contract should be examined by an expert to make certain all hold-harmless agreements are clearly stated and understood by both parties.

Any concern producing a product which may be dangerous to life or property has a legal responsibility to indicate the potential hazard by use of warning labels or other protective methods. The manufacturer must supply safe shipping containers and make certain that any hazards involved in their handling or use are clearly indicated. Legal liability also holds for defective or misrepresented products.

A manufacturing establishment may have on its property some object which would be highly attractive as a place for children to play. Two examples would be a quarry pit and a sand pile. An object of this type is known as an *attractive nuisance*, and the concern may be liable for injuries to children if the injuries are a result of their playing around or in the object. The liability would apply even though the children were obviously trespassing. High fences or some other effective safety measure should be used to keep children from gaining admittance to an attractive nuisance.

An industrial concern has a legal responsibility for property belonging to others as long as the property is on the concern's premises. This responsibility is known as a *bailee's liability*. The property may be stored equipment or materials, finished products, or products in process. If the property is damaged or destroyed, the bailee's liability is roughly a function of the degree of care used in safeguarding the property. In case the damaged or destroyed property is insured by the owner, the insurance company will pay the claim; however, the insurance company can then exercise its *subrogation rights* and attempt to force the bailee to pay the full amount received by the owner.

Types of Insurance

Many different types of insurance are available for protection against property loss or charges based on legal liability. Despite every precaution, there is always the possibility of an unforeseen event causing a sudden drain on a company's finances, and an efficient management protects itself against such potential emergencies by taking out insurance. In order to make an intelligent analysis of insurance requirements for any kind of operation, it is necessary to understand the physical factors involved in carrying out the process and to be aware of the types of insurance available.*

The major insurance requirements for manufacturing concerns can be classified as follows:

1. Fire insurance and similar emergency coverage on buildings, equipment, and all other owned, used, or stored property. Included in this category would be losses caused by lightning, wind- or hailstorms, floods, automobile accidents, explosions, earthquakes, and similar occurrences.
2. Public-liability insurance, including bodily injury and property loss or damage, on all operations such as those involving automobiles, elevators, attractive nuisances, bailee's charges, aviation products, or any company function carried on at a location away from the plant premises.
3. Business-interruption insurance. The loss of income due to a business interruption caused by a fire or other emergency may far exceed any loss in property. Consequently, insurance against a business interruption of this type should be given careful consideration.
4. Power-plant, machinery, and special-operations hazards.
5. Workmen's-compensation insurance.
6. Marine and transportation insurance on all property in transit.
7. Comprehensive crime coverage.
8. Employee-benefit insurance, including life, hospitalization, accident, health, personal property, and pension plans.

Self-insurance. On an average basis, insurance companies pay out loss claims amounting to 55 to 60 cents for each dollar received. The balance is used for income taxes, salaries, commissions, administrative costs, inspection costs, and various overhead costs. Theoretically, a saving of 40 to 45 cents per dollar paid for insurance could be achieved by self-insurance. If insurance requirements are great, this saving could amount to a very large sum, and it would be worthwhile to consider the possibilities of self-insurance.

A careful analysis of all risks involved is necessary when considering self-insurance on possible losses or emergencies. The final decision should not be based on whether or not the insurable event will occur, since this is impossible to predict. Instead, the decision should be based on the total loss involved if the event or a series of such events were to occur. If an industrial concern has a number of widespread interests and sufficient funds available to handle simultaneous major losses in several of these interests, it might be reasonable to consider self-insurance on some of the potential hazards. On the other hand, if a single potential event could ruin the economic standing of the company, it would be very inadvisable to assume the risk involved in self-insurance.

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* For a detailed discussion of the different types of insurance, see J. H. Perry, "Chemical Business Handbook," McGraw-Hill Book Company, Inc., New York, 1954.

There are several different ways of applying self-insurance. One method involves depositing money equivalent to an insurance premium into a special company fund. This fund can then be used to handle any losses or emergencies which may occur. At the outset, this fund would be small and would be inadequate to handle any major losses. Consequently, if this method is used, it may be necessary to supply an original base fund or else assume a disproportionate amount of risk until the fund has built up to a practical value. Under ordinary conditions, the premiums paid into a self-insurance reserve are not tax-deductible.

A second method may be used in which the company assumes all the risk and no payments are made into a reserve fund. This method is designated as "self-assumption of risk." Partial self-insurance may be obtained through the purchase of deductible insurance from regular agencies. The purchaser assumes the risk up to a certain amount and the insurance company agrees to pay for any additional losses.

The effects of income taxes should be considered when making a final decision regarding insurance. Since the premiums for standard insurance are tax-deductible, the actual cost after taxes for the protection may be much less than the direct premium charge. Another advantage of standard insurance is the inspection services supplied by the insurance companies. These companies require periodic inspections by specialists to make certain that the insurance rates are adequate, and the reports of these inspectors often indicate new ideas or methods for increasing the safety of the operation.

The over-all policies of the particular manufacturing concern dictate the type and amount of insurance which will be held. It should be realized, however, that a well-designed insurance plan requires a great deal of skilled and informed investigation by persons who understand all the aspects of insurance as well as the problems involved in the manufacturing operation.

PROBLEMS

1. The fixed-capital investment for an existing chemical plant is \$20 million. Annual property taxes amount to 1 per cent of the fixed-capital investment, and state income taxes are 5 per cent of the gross earnings. The net income per year after all taxes is $2 million, and the Federal income taxes amount to 52 per cent of gross earnings. If the same plant had been constructed at a location where property taxes were 4 per cent of the fixed-capital investment and state income taxes were 2 per cent of the gross earnings, what would be the net income per year after taxes, assuming all other cost factors were unchanged?

2. The gross earnings for a small corporation were $54,000 in 1955. What would have been the per cent reduction in Federal income taxes paid by the company if the proposed reduction of the normal tax from 30 to 25 per cent had been approved? (Surtax was 22 per cent of all gross earnings above $25,000.)

3. During the period of one taxable year at a manufacturing plant, the total income on a cash basis was $21 million. Five million dollars of immediate debts due the company was unpaid at the end of the year. The company paid out $15 million on a cash basis during the year, and all of this amount was tax-deductible as a product cost. The company still owed $3 million of tax-deductible bills at the end of the year. If the total Federal income tax for the company amounts to 48 per cent of the gross earnings, determine the amount of Federal income tax due for the year on a cash basis and also on an accrual basis.

4. Complete fire and allied-coverage insurance for one unit of a plant requires an annual payment of $700 based on an investment value of $100,000. If income taxes over a 10-year period average 40 per cent of gross earnings, by how much is the net income, after taxes, reduced during this 10-year period owing to the cost of the insurance?

5. Self-insurance is being considered for one portion of a chemical company. The fixed-capital investment involved is $50,000, and insurance costs for complete protection would amount to $400 per year. If self-insurance is used, a reserve fund will be set up under the company's jurisdiction, and annual insurance premiums of $300 will be deposited in this fund under an ordinary annuity plan. All money in the fund can be assumed to earn interest at a compound annual rate of 3 per cent. Neglecting any charges connected with administration of the fund, how much money should be deposited in the fund at the beginning of the program in order to have enough money accumulated to replace a complete $50,000 loss after 10 years?

CHAPTER 5

DEPRECIATION

An analysis of costs and profits for any business operation requires recognition of the fact that physical assets decrease in value with age. This decrease in value may be due to physical deterioration, technological advances, economic changes, or other factors which ultimately will cause retirement of the property. The reduction in value due to any of these causes is a measure of the *depreciation*.* The economic function of depreciation, therefore, can be employed as a means of distributing the original expense for a physical asset over the period during which the asset is in use.

Because the engineer thinks of depreciation as a measure of the decrease in value of property with time, depreciation can immediately be considered from a cost viewpoint. For example, suppose a piece of equipment had been put into use 10 years ago at a total cost of $31,000. The equipment is now worn out and is worth only $1000 as scrap material. The decrease in value during the 10-year period is $30,000; however, the engineer recognizes that this $30,000 is in reality a cost incurred for the use of the equipment. This depreciation cost was spread over a period of 10 years, and sound economic procedure would require part of this cost to be charged during each of the years. The application of depreciation in engineering design, accounting, and tax studies is almost always based on costs prorated throughout the life of the property.

Meaning of Value. From the viewpoint of the design engineer, the total cost due to depreciation is the original or new value of a property minus the value of the same property at the end of the depreciation period. The original value is usually taken as the total cost of the property at the time it is ready for initial use. In engineering design practice, the total depreciation period is ordinarily assumed to be the length of the property's useful life, and the value at the end of the useful life is assumed to be the probable scrap or salvage value of the components making up the particular property.

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* According to the Bureau of Internal Revenue Code, depreciation is defined as "A reasonable allowance for the exhaustion, wear, and tear of property used in the trade or business, including a reasonable allowance for obsolescence." The terms *amortization* and *depreciation* are often used interchangeably. Amortization is usually associated with a definite period of cost distribution, while depreciation usually deals with an unknown or estimated period over which the asset costs are distributed.

It should be noted here that the engineer cannot wait until the end of the depreciation period to determine the depreciation costs. These costs must be prorated throughout the entire life of the property, and they must be included as an operating charge incurred during each year. The property value at the end of the depreciation period and the total length of the depreciation period cannot be known with certainty when the initial yearly costs are determined. Consequently, it is necessary to estimate the final value of the property as well as its useful life. In estimating the property life, the various factors which may affect the useful-life period, such as wear and tear, economic changes, or possible technological advances, should be taken into consideration.

When depreciation is not used in a prorated-cost sense, various meanings can be attached to the word *value*. One of these meanings involves appraisal of both initial and final values on the basis of conditions at a certain time. The difference between the estimated cost of new equivalent property and the appraised value of the present asset is known as the *appraised depreciation*. This concept involves determination of the values of two assets at one date as compared with the engineering-cost concept, which requires determination of the value of one asset at two different times.[*]

Purpose of Depreciation. There are two major reasons why depreciation needs to be considered in engineering projects. As far as the design engineer is concerned, the primary purpose of depreciation is to permit the proper charging of costs for physical assets in determining production costs and profits. A second purpose of depreciation is to provide for the allocation of capital which has been invested in physical property.

TYPES OF DEPRECIATION

The causes of depreciation may be physical or functional. *Physical depreciation* is the term given to the measure of the decrease in value due to changes in the physical aspects of the property. Wear and tear, corrosion, accidents, and deterioration due to age or the elements are all causes of physical depreciation. With this type of depreciation, the serviceability of the property is reduced because of physical changes. Depreciation due to all other causes is known as *functional depreciation.*

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[*] For further information on the possible meanings of depreciation when used in a sense other than that of the engineers' prorated (or amortized) cost, see E. Grant and P. Norton, "Depreciation," The Ronald Press Company, New York, 1949; or A. Marston, R. Winfrey, and J. Hempstead, "Engineering Valuation and Depreciation," 2d ed., McGraw-Hill Book Company, Inc., New York, 1953.

One common type of functional depreciation is *obsolescence*. This is caused by technological advances or developments which make an existing property obsolete. Even though the property has suffered no physical change, its economic serviceability is reduced because it is inferior to improved types of similar assets that have been made available through advancements in technology.

Other causes of functional depreciation could be (1) change in demand for the service rendered by the property, such as a decrease in the demand for the product involved because of saturation of the market, (2) shift of population center, (3) changes in requirements of public authority, (4) inadequacy or insufficient capacity for the service required, (5) termination of the need for the type of service rendered, and (6) abandonment of the enterprise. Although some of these situations may be completely unrelated to the property itself, it is convenient to group them all under the heading of functional depreciation.

Since depreciation is measured by decrease in value, it is necessary to consider all possible causes when determining depreciation. Physical losses are easier to evaluate than functional losses, but both of these must be taken into account in order to make fair allowances for depreciation.

Depletion. Capacity loss due to materials actually consumed is measured as *depletion*. Depletion cost equals the initial cost times the ratio of amount of material used to original amount of material purchased. This type of depreciation is particularly applicable to natural resources, such as stands of timber or mineral and oil deposits.

Costs for Maintenance and Repairs. The term *maintenance* conveys the idea of constantly keeping a property in good condition; *repairs* connotes the replacing or mending of broken or worn parts of a property. The costs for maintenance and repairs are direct operating expenses which must be paid from income, and these costs should not be confused with depreciation costs.

The extent of maintenance and repairs may have an effect on depreciation cost, since the useful life of any property ought to be increased if it is kept in good condition. However, a definite distinction should always be made between costs for depreciation and costs for maintenance and repairs.

SERVICE LIFE

The period during which the use of a property is economically feasible is known as the *service life* of the property. Both physical and functional depreciation are taken into consideration in determining service life, and, as used in this book, the term is synonymous with *economic life* or *useful life*. In estimating the probable service life, it is assumed that a reasonable amount of maintenance and repairs will be carried out at the expense of the property owner.

Many data are available concerning the probable life of various types of property. Manufacturing concerns, engineers, and the U.S. Bureau of Internal Revenue have compiled much information of this sort. All of these data are based on past records, and there is no certainty future conditions will be unchanged. Nevertheless, by statistical analysis of the various data, it is possible to make fairly reliable estimates of service lives.

TABLE 1. PROBABLE SERVICE LIVES FOR PROPERTIES IN THE CHEMICAL INDUSTRIES *

These estimates are for new properties only. Due consideration has been given to normal obsolescence possibilities. Reasonable expenses for repairs and maintenance have been assumed. See Appendix for a detailed breakdown of service lives for individual pieces of equipment in the different chemical industries.

	Service life, years
Machinery and equipment:	
Acids	15
Alkaline products	22
Aniline dyes	20
Atmospheric nitrogen	15
Brewery products	20
Carbide and carbon products	15
Carbonic gas products	16
Cement products	20
Chromium products	15
Coal-tar products	20
Distillation products	20
Electrochemicals	17
Glass products	15
Oxygen products	18
Paints and varnishes	20
Pharmaceuticals	20
Rubber products	17
Soap	20
Buildings:	
Dwellings	60
Factory buildings	50
Garages	60
Machine shops	60
Office buildings	67
Stores	67
Warehouses	75

* Taken from *U.S. Bureau of Internal Revenue Bull. F*, 1942.

The U.S. Bureau of Internal Revenue recognizes the importance of depreciation as a legitimate expense, and the Bureau has issued a formal bulletin listing recommended service lives for many types of properties.*

Table 1 presents the probable service lives for machinery and equipment in the chemical industries. Although these values are recommended by the Bureau of Internal Revenue, the Bureau does not require taxpayers to use the indicated lives. However, if other life periods are used, the taxpayer must be prepared to support his claim.

There has been considerable demand for a reduction or wider choice of service lives for properties, and the widespread revision and reinterpretation of the national income-tax laws in 1954 met part of this demand. During times of national emergencies, the United States Congress may approve rapid-amortization policies to make it more attractive for concerns to invest in additional plants and equipment needed for the national welfare. Certificates of necessity can be obtained for certain types of industries, and these certificates permit writing off various percentages of the value of new equipment and facilities over a period of 5 years.

SALVAGE VALUE

Salvage value is the net amount of money obtainable from the sale of used property over and above any charges involved in removal and sale. If a property is capable of further service, its salvage value may be high. This is not necessarily true, however, because other factors, such as location of the property, existing price levels, market supply and demand, and difficulty of dismantling, may have an effect. The term *salvage value* implies that the asset can give some type of further service and is worth more than merely its scrap or junk value.

If the property cannot be disposed of as a useful unit, it can often be dismantled and sold as junk to be used again as a manufacturing raw material. The profit obtainable from this type of disposal is known as the *scrap*, or *junk, value.*

Salvage value, scrap value, and service life are usually estimated on the basis of conditions at the time the property is put into use. These factors cannot be predicted with absolute accuracy, but improved estimates can be made as the property increases in age. It is advisable, therefore, to make new estimates from time to time during the service life and make any necessary adjustments of the depreciation costs. Because of the difficulties involved in making reliable, future estimates of salvage and scrap values, engineers often neglect the small error involved and designate these values as zero.

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* Bulletin F, revised in 1931 and 1942, Income Tax Depreciation and Obsolescence—Estimated Useful Lives and Depreciation Rates, U.S. Treasury Department, Bureau of Internal Revenue.

PRESENT VALUE

The *present value* of an asset may be defined as the value of the asset in its condition at the time of valuation. There are several different types of present values, and the standard meanings of the various types should be distinguished.

Book Value, or Unamortized Cost. The difference between the original cost of a property and all the depreciation charges made to date is defined as the *book value* (sometimes called *unamortized cost*). It represents the worth of the property as shown on the owner's accounting records.

Market Value. The price which could be obtained for an asset if it were placed on sale in the open market is designated as the *market value*. The use of this term conveys the idea that the asset is in good condition and that a buyer is readily available.

Replacement Value. The cost necessary to replace an existing property at any given time with one at least equally capable of rendering the same service is known as the *replacement value*.

It is difficult to predict future market values or replacement values with a high degree of accuracy because of fluctuations in market demand and price conditions. On the other hand, a future book value can be predicted with absolute accuracy as long as a constant method for determining depreciation costs is used. It is quite possible for the market value, replacement value, and book value of a property to be widely different from one another because of unrealistic depreciation allowances or changes in economic and technological factors.

METHODS FOR DETERMINING DEPRECIATION

Depreciation costs can be determined by a number of different methods, and the design engineer should understand the bases for the various methods. The Federal government has definite rules and regulations concerning the manner in which depreciation costs may be determined. These regulations must be followed for income-tax purposes as well as to obtain most types of governmental support. Since the methods approved by the government are based on sound economic procedures, most industrial concerns use one of the government-sanctioned methods for determining depreciation costs, both for income-tax calculations and for reporting the concern's costs and profits. It is necessary, therefore, for the design engineer to keep abreast of current changes in governmental regulations regarding depreciation allowances.

In general, depreciation accounting methods may be divided into two classes: (1) arbitrary methods giving no consideration to interest costs, and (2) methods taking into account interest on the investment. Straight-line, declining-balance, and sum-of-the-years-digits methods are included in the first class, while the second class includes the sinking-fund and the present-worth methods.

Straight-line Method. In the *straight-line method* for determining depreciation, it is assumed that the value of the property decreases linearly with time. Equal amounts are charged for depreciation each year throughout the entire service life of the property. The annual depreciation cost may be expressed in equation form as follows:

$$d = \frac{V - V_s}{n} \tag{1}$$

where d = annual depreciation, \$/year
V = original value of the property at start of the service-life period, completely installed and ready for use, dollars
V_s = salvage value of property at end of service life, dollars
n = service life, years

The asset value (or book value) of the equipment at any time during the service life may be determined from the following equation:

$$V_a = V - ad \tag{2}$$

where V_a = asset or book value, dollars, and a = the number of years in actual use.

Because of its simplicity, the straight-line method is widely used for determining depreciation costs. In general, design engineers report economic evaluations on the basis of straight-line depreciation unless there is some specific reason for using one of the other methods.

Because it is impossible to estimate exact service lives and salvage values when a property is first put into use, it is sometimes desirable to reestimate these factors from time to time during the life period of the property. If this is done, straight-line depreciation can be assumed during each of the periods, and the over-all method is known as *multiple straight-line depreciation*. Figure 5-1 shows how the asset value of a property varies with time using the straight-line and the multiple straight-line methods for determining depreciation.

The straight-line method may be applied on the basis of units of production or predicted amount of service output, instead of life years. The depreciation may be based on miles, gallons, tons, number of unit pieces produced, or other measures of service output. This so-called *unit-of-production* or *service-output* method is particularly applicable when depletion occurs, as in the exploitation of natural resources. It should also be considered for properties having useful lives that are more dependent on the number of operations performed than on calendar time.

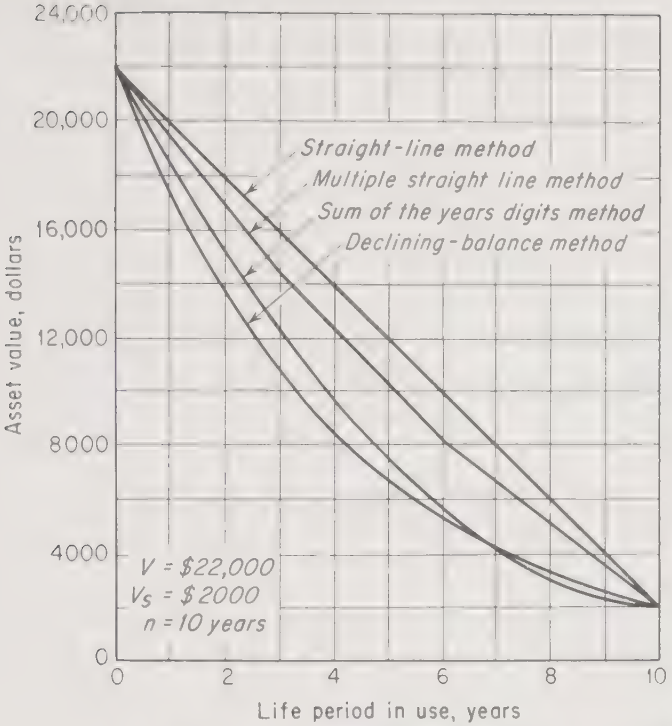

FIG. 5-1. Comparison of straight-line, sum-of-the-years-digits, and declining-balance methods for determining depreciation.

Declining-balance (or Fixed-percentage) Method. When the declining-balance method is used, the annual depreciation cost is a fixed percentage of the property value at the beginning of the particular year. The fixed-percentage (or declining-balance) factor remains constant throughout the entire service life of the property, while the annual cost for depreciation is different each year. Under these conditions, the depreciation cost for the first year of the property's life is $V\mathfrak{f}$, where $\mathfrak{f}$ represents the fixed-percentage factor.

At the end of the first year

$$\text{Asset value} = V_a = V(1 - \mathfrak{f}) \tag{3}$$

At the end of the second year

$$V_a = V(1 - \mathfrak{f})^2 \tag{4}$$

At the end of a years

$$V_a = V(1 - \mathfrak{f})^a \tag{5}$$

At the end of n years (i.e., at the end of service life)

$$V_a = V(1 - \mathfrak{f})^n = V_s \tag{6}$$

Therefore,

$$\mathfrak{f} = 1 - \left(\frac{V_s}{V}\right)^{1/n} \tag{7}$$

Equation (7) represents the textbook method for determining the fixed-percentage factor, and the equation is sometimes designated as the *Matheson formula*. A plot showing the change of asset value with time using the declining-balance depreciation method is presented in Fig. 5-1. Comparison with the straight-line method shows that declining-balance depreciation permits the investment to be paid off more rapidly during the early years of life. The increased depreciation costs in the early years are very attractive to concerns just starting in business, since the income-tax load is reduced at the time when it is most necessary to keep all pay-out costs at a minimum.

The textbook relationship presented in Eq. (7) is seldom used in actual practice, because it places too much emphasis on the salvage value of the property and is certainly not applicable if the salvage value is zero. To overcome this disadvantage, the value of the fixed-percentage factor is often chosen arbitrarily using a sound economic basis.

Prior to 1954, the United States government would not accept any depreciation method which permitted depreciation rates more than 50 per cent greater than those involved in the straight-line method. In 1954, the laws were changed to allow rates up to twice those for the straight-line method. Under these conditions, one arbitrary method for choosing the value of $\mathfrak{f}$ is to fix it at two times the reciprocal of the service life n.* This permits approximately two-thirds of the depreciable value to be written off in the first half of the useful life.

Figure 5-2 shows the effect of time on asset value when the declining-balance method of depreciation is used with an arbitrarily chosen value of $\mathfrak{f}$. It should be noted that the value of the asset cannot decrease to zero at the end of the service life and may possibly be greater than the salvage or scrap value. To handle this difficulty, it is sometimes desirable to switch from the declining-balance to the straight-line method after a portion of the service life has expired. This is known as the *combination method*. It permits the property to be fully depreciated during the service life, yet also gives the advantage of faster early-life write-offs. A curve showing this type of depreciation is presented in Fig. 5-2.

The main advantage of the declining-balance and the combination methods is that they permit greater depreciation allowances in the early life of the property than in the later life. They are particularly applicable for units in which the greater proportion of the production occurs in the

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* The salvage value is considered to be zero, and the fixed-percentage factor is based on the straight-line rate of depreciation during the first year.

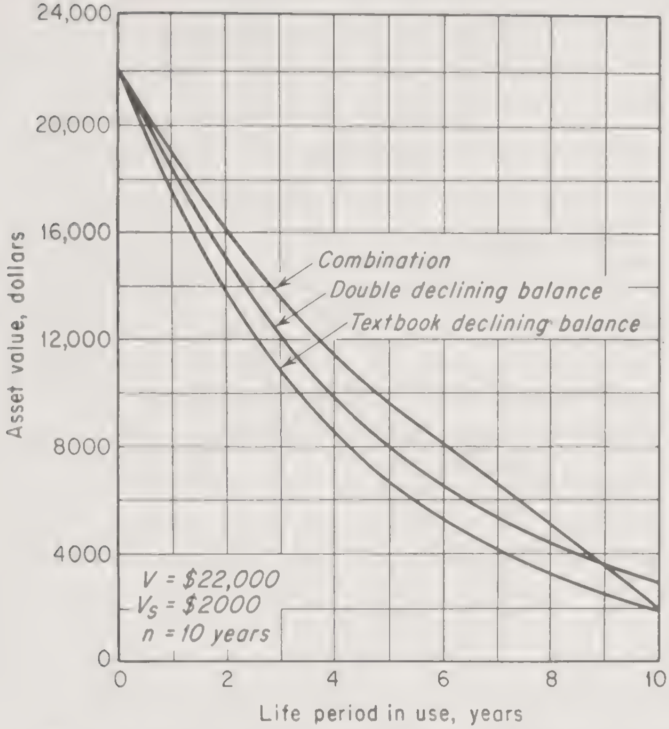

FIG. 5-2. Types of declining-balance methods for determining depreciation.

early part of the useful life or when operating costs increase markedly with age.

Example 1. Determination of Depreciation by Straight-line and Declining-balance Methods. The original value of a piece of equipment is \$22,000, completely installed and ready for use. Its salvage value is estimated to be \$2000 at the end of a service life estimated to be 10 years. Determine the asset (or book) value of the equipment at the end of 5 years using:

(*a*) Straight-line method.

(*b*) Textbook declining-balance method.

(*c*) Double declining-balance method (i.e., the declining-balance method using a fixed-percentage factor giving a depreciation rate equivalent to twice the minimum rate with the straight-line method).

Solution

(*a*) Straight-line method:

$V = \$22{,}000$

$V_s = \$2000$

$n = 10$ years

$$d = \frac{V - V_s}{n} = \frac{20{,}000}{10} = \$2000 \text{ per year}$$

Asset value after 5 years $= V_a$, where $a = 5$, or

$$V_a = V - ad = 22{,}000 - (5)(2000) = \$12{,}000$$

(*b*) Textbook declining-balance method:

$$\mathfrak{f} = 1 - \left(\frac{V_s}{V}\right)^{1/n} = 1 - \left(\frac{2000}{22{,}000}\right)^{1/10} = 0.2131$$

Asset value after 5 years is

$$V_a = V(1 - \mathfrak{f})^a = (22{,}000)(1 - 0.2131)^5 = \$6650$$

(*c*) Double declining-balance method:

Using the straight-line method, the minimum depreciation rate occurs in the first year when $V = \$22{,}000$ and the depreciation $= \$2000$. This depreciation rate is 2000/22,000, and the double declining-balance (or double fixed-percentage) factor is $(2)(2000/22{,}000) = 0.1818 = \mathfrak{f}$. (It should be noted that the double declining-balance method is often applied to cases where the salvage value is considered to be zero. Under this condition, the double fixed-percentage factor for this example would be 0.2000.)

Asset value after 5 years is

$$V_a = V(1 - \mathfrak{f})^a = (22{,}000)(1 - 0.1818)^5 = \$8060$$

Sum-of-the-years-digits Method. The *sum-of-the-years-digits method* is an arbitrary process for determining depreciation which gives results similar to those obtained by the declining-balance method. Larger costs for depreciation are allotted during the early-life years than during the later years. This method has the advantage of permitting the asset value to decrease to zero or a given salvage value at the end of the service life.

In the application of the sum-of-the-years-digits method, the annual depreciation is based on the number of service-life years remaining and the sum of the arithmetic series of numbers from 1 to n, where n represents the total service life. The yearly depreciation factor is the number of useful service-life years remaining divided by the sum of the arithmetic series. This factor times the total depreciable value at the start of the service life gives the annual depreciation cost.

As an example, consider the case of a piece of equipment costing \$20,000 when new. The service life is estimated to be 5 years and the scrap value \$2000. The sum of the arithmetic series of numbers from 1 to n is $1 + 2 + 3 + 4 + 5 = 15$. The total depreciable value at the start of the service life is $\$20{,}000 - \$2000 = \$18{,}000$. Therefore, the depreciation cost for the first year is $(\$18{,}000)(5/15) = \$6000$, and the asset value at the end of the first year is \$14,000. The depreciation cost for the second year is $(\$18{,}000)(4/15) = \$4800$. Similarly, the depreciation costs for the third, fourth, and fifth years, respectively, would be \$3600, \$2400, and \$1200. Figure 5-1 presents a curve showing the change with time in asset value when the sum-of-the-years-digits method is used for determining depreciation.

Sinking-fund Method. The use of compound interest is involved in the *sinking-fund method*. It is assumed that the basic purpose of depreciation allowances is to accumulate a sufficient fund to provide for the recovery of the original capital invested in the property. An ordinary annuity plan is set up wherein a constant amount of money should theoretically be set aside each year. At the end of the service life, the sum of all the deposits plus accrued interest must equal the total amount of depreciation.

Derivation of the formulas for the sinking-fund method can be accomplished by use of the following notations in addition to those already given:

i = annual interest rate expressed as a fraction
R = uniform annual payments made at end of each year (this is the annual depreciation cost), dollars
$V - V_s$ = total amount of the annuity accumulated in an estimated service life of n years (original value of property minus salvage value at end of service life), dollars

According to the equations developed for an ordinary annuity in Chap. 3 (Interest and Investment Costs),

$$R = (V - V_s)\frac{i}{(1 + i)^n - 1} \tag{8}$$

The amount accumulated in the fund after a years of useful life must be equal to the total amount of depreciation up to that time. This is the same as the difference between the original value of the property V at the start of the service life and the asset value V_a at the end of a years. Therefore,

$$\text{Total amount of depreciation after } a \text{ years} = V - V_a \tag{9}$$

$$V - V_a = R\frac{(1 + i)^a - 1}{i} \tag{10}$$

Combining Eqs. (8) and (10),

$$V - V_a = (V - V_s)\frac{(1 + i)^a - 1}{(1 + i)^n - 1} \tag{11}$$

Asset (or book) value after a years = V_a

$$V_a = V - (V - V_s)\frac{(1 + i)^a - 1}{(1 + i)^n - 1} \tag{12}$$ *

Since the value of R represents the annual depreciation cost, the yearly cost for depreciation is constant when the sinking-fund method is used.

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* Exactly the same result for asset value after a years is obtained if an annuity due (i.e., equal periodic payments at beginning of each year) is used in place of an ordinary annuity. The periodic payment with an annuity due would be $R/(1 + i)$. In accepted engineering practice, the sinking-fund method is based on an ordinary annuity plan

As shown in Fig. 5-3, this method results in book values which are always greater than those obtained with the straight-line method. Because of the effects of interest in the sinking-fund method, the annual decrease in asset value of the property is less in the early-life years than in the later years.

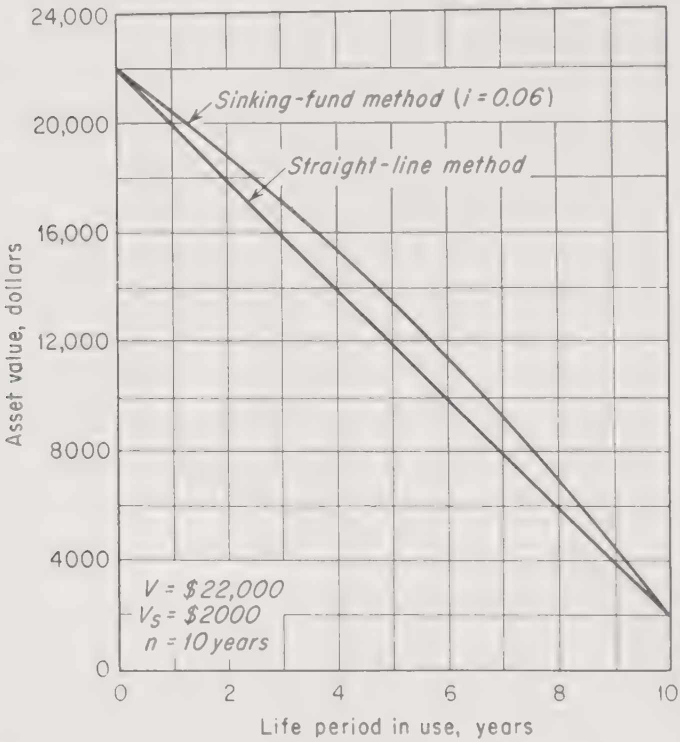

FIG. 5-3. Asset values of property when depreciated by interest (sinking-fund) and no-interest (straight-line) methods.

Although the sinking-fund viewpoint assumes the existence of a fund into which regular deposits are made, an actual fund is seldom maintained. Instead, the money accumulated from the depreciation charges is put to work in other interests, and the existence of the hypothetical fund merely serves as a basis for this method of depreciation accounting.

The sinking-fund theory of cost accounting is now used by only a few concerns, although it has seen considerable service in the public-utilities field. Theoretically, the method would be applicable for depreciating any property that did not undergo heavy service demands during its early life and stood little chance of becoming obsolete or losing service value due to other functional causes.

The same approach used in the sinking-fund method may be applied by analyzing depreciation on the basis of reduction with time of future profits obtainable with a property. When this is done, it is necessary to use an interest rate equivalent to the annual rate of return expected from the use of the property. This method is known as the *present-worth method*, and it gives results similar to those obtained with the conventional sinking-fund approach.* The sinking-fund and the present-worth methods are seldom used for depreciation cost accounting, but they are occasionally applied for purposes of comparing alternative investments.

SINGLE-UNIT AND GROUP DEPRECIATION

In depreciation accounting procedures, assets may be depreciated on the basis of individual units or on the basis of various types of property groups or classifications. The *single-unit method* requires keeping records on each individual asset. Although the application of this method is simple, the large number of detailed records required makes the accounting expenses very high.

To simplify the accounting procedures, many concerns combine their various assets into groups for depreciation purposes. There are several types of group accounts employed, and the most common among these are composite accounts, classified accounts, and vintage-group accounts.

A *composite account* includes all depreciable assets in one single group, and an over-all depreciation rate is applied to the entire account. With this method, the composite depreciation rate must be redetermined when important changes occur in the relative distribution of the service lives of the individual assets.

Instead of including all assets in a single depreciation account, it is possible to classify properties into general types, such as machinery and equipment, office furniture and fixtures, buildings, and transportation equipment. The records for these groups are known as *classified accounts*. A classified account is similar to a composite account because many items are included in the same group, regardless of life characteristics.

Another approach to group depreciation is to include in each account all similar assets having approximately the same service lives. These accounts are known as *vintage-group accounts*. A separate record is kept for each group and the same depreciation rate is applied to all the items included in each account. With this method, the advantages of single-unit depreciation are obtained since life characteristics serve as the basis. If a large number of items are contained in a vintage-group account, the over-all depreciation results can be quite accurate because the law of averages will apply to the true service lives as compared with the estimated service lives.

* For a detailed treatment of the present-worth method, see A. Marston, R. Winfrey, and J. C. Hempstead, "Engineering Valuation and Depreciation," McGraw-Hill Book Company, Inc., New York, 1953.

ADJUSTMENT OF DEPRECIATION ACCOUNTS

The estimated service life and salvage value of a property are seldom exactly equal to the actual service life and salvage value. It is, therefore, advisable to adjust depreciation accounts by making periodic reestimations of the important variables. When a property is retired under conditions which do not permit exact agreement between estimated and actual values, the difference between the book depreciation and the actual depreciation may be handled in one of the following ways: (1) The gain or loss may be credited or charged on the financial record for the current period; (2) the difference may be credited or charged to a special depreciation reserve; or (3) the difference may be carried on the books for amortization during a reasonable future period.

According to the Federal income-tax laws in effect in 1956, any gain on the retirement of a property is taxed as a capital gain. However, losses cannot be subtracted from the taxable income unless the maximum expected life was used. Because of the losses involved when a property must be retired before the end of its estimated service life, some concerns prefer to use a combination of methods 2 and 3 indicated in the preceding paragraph. A special depreciation reserve is built up by continuing the book depreciation of properties whose actual service lives exceed the estimated service lives. This fund is then used to handle losses due to early retirement of assets. The final choice of method for adjusting depreciation accounts depends on the accounting policies of the individual concern and on income-tax regulations.

EVALUATION OF DEPRECIATION METHODS

Comparison of the various depreciation methods shows that the declining-balance and the sum-of-the-years-digits methods give similar results. In both cases, the depreciation costs are greater in the early-life years of the property than in the later years. Annual depreciation costs are constant when the straight-line, sinking-fund, or present-worth method is used. Because interest effects are included in the sinking-fund and present-worth methods, the annual decrease in asset value with these two methods is lower in the early-life years than in the later years.

The straight-line method is widely used for depreciation cost accounting. It is very simple to apply, to both groups and single units, and it is acceptable for cost-accounting purposes and for income-tax determinations. In general, unless there is a specific reason for employing another method, design engineers use straight-line depreciation.

From the viewpoint of financial protection, it is desirable to make a greater charge for property depreciation during early life than during later life. This can be accomplished by use of the declining-balance or sum-of-the-years-digits method. The difficulties of accurate application to group accounts and income-tax restrictions have served to suppress the widespread usage of these methods. However, in recent years, a number of industrial concerns have started using declining-balance and sum-of-the-years-digits depreciation.

The liberalized tax laws passed in 1954 permitted use of double declining-balance depreciation as well as sum-of-the-years-digits depreciation for income-tax calculations. In general, these laws gave approval to any depreciation method which did not give faster write-offs at any point during the first two-thirds of an asset's useful life than the double declining-balance method. The 1954 laws applied only to assets put in use after Jan. 1, 1954, and the new regulations were not applicable to assets with service lives of less than 3 years.

The final choice of the best depreciation method depends on a number of different factors. The type and function of the property involved is, of course, one important factor. Also, it is desirable to use a simple formula giving results as accurate as the estimated values involved. The advisability of keeping two separate sets of books, one for income-tax purposes and one for company purposes, should be considered. The final decision involves application of good judgment and an analysis of the existing circumstances.

NOMENCLATURE FOR CHAP. 5

a = length of time in actual use, years
d = annual depreciation, $/year
f = fixed-percentage or declining-balance factor
i = annual interest rate expressed as a fraction, per cent/100
n = service life, years
R = uniform annual payments made in an ordinary annuity, dollars
V = original value of a property at start of service-life period, completely installed and ready for use, dollars
V_a = asset or book value, dollars
V_s = salvage value of property at end of service life, dollars

PROBLEMS

1. A piece of equipment originally costing $40,000 was put into use 12 years ago. At the time the equipment was put into use, the service life was estimated to be 20 years and the salvage and scrap value at the end of the service life were assumed to be zero. On this basis, a straight-line depreciation fund was set up. The equipment can now be sold for $10,000, and a more advanced model can be installed for $55,000. Assuming the depreciation fund is available for use, how much new capital must be supplied to make the purchase?

2. The original investment for an asset was $10,000, and the asset was assumed to have a service life of 12 years with $2000 salvage value at the end of the service life. After the asset has been in use for 5 years, the remaining service life and final salvage value are reestimated at 10 years and $1000, respectively. Under these conditions, what is the depreciation cost during the sixth year of the total life if straight-line depreciation is used?

3. A property has an initial value of \$50,000, service life of 20 years, and final salvage value of \$4000. It has been proposed to depreciate the property by the textbook declining-balance method. Would this method be acceptable for income-tax purposes if the income-tax laws do not permit annual depreciation rates greater than twice the minimum annual rate with the straight-line method?

4. A piece of equipment having a negligible salvage and scrap value is estimated to have a service life of 10 years. The original cost of the equipment was \$40,000. Determine the following:

(*a*) The depreciation charge for the fifth year if double declining-balance depreciation is used.

(*b*) The depreciation charge for the fifth year if sum-of-the-years-digits depreciation is used.

(*c*) The per cent of the original investment paid off in the first half of the service life using the double declining-balance method.

(*d*) The per cent of the original investment paid off in the first half of the service life using the sum-of-the-years-digits method.

5. The original cost of a property is \$30,000, and it is depreciated by a 6 per cent sinking-fund method. What is the annual depreciation charge if the book value of the property after 10 years is the same as if it had been depreciated at \$2500 per year by the straight-line method?

6. A concern has a total income of \$1 million per year, and all expenses except depreciation amount to \$600,000 per year. At the start of the first year of the concern's operation, a composite account of all depreciable items shows a value of \$850,000, and the over-all service life is estimated to be 20 years. The total salvage value at the end of the service life is estimated to be \$50,000. Forty-five per cent of all profits before taxes must be paid out as income taxes. What would be the reduction in income-tax charges for the first year of operation if the sum-of-the-years-digits method were used for depreciation accounting instead of the straight-line method?

7. The total value of a new plant is \$2 million. A certificate of necessity has been obtained permitting a write-off of 60 per cent of the initial value in 5 years. The balance of the plant requires a write-off period of 15 years. Using the straight-line method and assuming negligible salvage and scrap value, determine the total depreciation cost during the first year.

8. A profit-producing property has an initial value of \$50,000, a service life of 10 years, and zero salvage and scrap value. By how much would annual profits before taxes be increased if a 5 per cent sinking-fund method were used to determine depreciation costs instead of the straight-line method?

9. In order to make it worthwhile to purchase a new piece of equipment, the annual depreciation costs for the equipment cannot exceed \$3000 at any time. The original cost of the equipment is \$30,000, and it has zero salvage and scrap value. Determine the length of service life necessary if the equipment is depreciated (*a*) by the sum-of-the-years-digits method, and (*b*) by the straight-line method.

10. The owner of a property is using the unit-of-production method for determining depreciation costs. The original value of the property is \$55,000. It is estimated that this property can produce 5500 units before its value is reduced to zero; i.e., the depreciation cost per unit produced is \$10. The property produces 100 units during the first year, and the production rate is doubled each year for the first 4 years. The production rate obtained in the fourth year is then held constant until the value of the property is paid off. What would have been the annual depreciation cost if the straight-line method based on time had been used?

CHAPTER 6

ALTERNATIVE INVESTMENTS AND REPLACEMENTS

Before capital is invested in a project or enterprise, it is necessary to know if a profit can be realized by making the investment. It is also necessary to know how much profit can be obtained and whether it would be more advantageous to invest the capital in another form of enterprise. Thus, the determination of profits obtainable from the investment of capital and the choice of the best investment among various alternatives is an important part of an economic analysis.

Total profit alone cannot be used as the deciding factor in determining if an investment should be made. Instead, the decision should be based on the *rate of return* which the capital can yield. For example, suppose that two equally sound investments can be made. One of these requires \$100,000 of capital and will yield a profit of \$10,000 per year, and the second requires \$1 million of capital and will yield \$25,000 per year. The second investment gives a greater yearly profit than the first, but the annual rate of return on the second investment is only (\$25,000/\$1,000,000) × 100 = 2.5 per cent, while the annual rate of return on the \$100,000 investment is 10 per cent. Since reliable bonds and other conservative investments will yield annual rates of return in the range of 3 to 4 per cent, the \$1 million investment in this example would not be very attractive; however, the 10 per cent return on the \$100,000 capital would make this investment worthy of careful consideration. Thus, the rate of return, rather than the total amount of profit, is usually the deciding factor in determining if an investment should be made.

There are many reasons why capital investments are made. Sometimes the purpose is merely to supply a service which cannot possibly yield a monetary profit, such as the provision of recreation facilities for free use of employees. The per cent return on this type of venture cannot be expressed on any direct numerical basis. The design engineer, however, usually deals with the type of investment which is expected to yield a tangible profit.

Investments may be made for replacing or improving an existing property, for developing a completely new enterprise, or for other purposes wherein a profit is expected from the outlay of capital. In cases of this type, it is extremely important to make a careful analysis of the effectiveness of the capital utilization.

RETURN ON INVESTMENT

In engineering economic studies, return on investment is ordinarily expressed on an annual percentage basis. The yearly profit divided by the total initial investment necessary represents the fractional return, and this fraction times 100 is the *per cent return on the investment.**

Profit is defined as the difference between income and expense. Therefore, profit is a function of the quantity of goods or services produced and the selling price. The amount of profit is also affected by the economic efficiency of the operation, and increased profits can be obtained by use of effective methods which reduce operating expenses.

To obtain reliable estimates of investment returns, it is necessary to make accurate predictions of profits, basing these profits on the complete investment required. As discussed in Chap. 2 (Costs in Chemical Processes), working capital and fixed capital should be considered in determining the total investment, and direct production costs, fixed charges including depreciation costs, plant overhead costs, and general expenses are involved in the determination of profits.†

Returns Incorporating Minimum Profits as an Expense. The standard method for reporting return on investment has been outlined in the preceding paragraphs. Other methods, however, are sometimes employed, and their bases should be understood to permit correct interpretation if they are encountered.

One method for reporting return on investment is based on the assumption that it must be possible to obtain a certain minimum profit or return from an investment before the necessary capital outlay will be desirable. This minimum profit is included as a fictitious expense along with the other standard expenses. When return on investment is determined in this manner, the result shows the *risk earning rate*, and it represents the return over and above that necessary to make the capital expenditure advisable. If the return is zero or larger, the investment will be attractive. This method is sometimes designated as *return based on capital recovery with minimum profit.*

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* Returns are sometimes expressed on the basis of average book value of the fixed-capital investment over the useful life plus working capital.

† Under some conditions, the return on investment can be based on the fixed-capital investment instead of the total investment. Profit may be expressed on a before-tax or after-tax basis, but the conditions should be indicated. Other bases occasionally used by engineers for reporting rate of return as profit are net sales, total liabilities, and net worth. For a detailed treatment of various methods for reporting returns and an analysis of theoretical methods for including the time value of money in return calculations, see H. E. Schweyer, "Process Engineering Economics," McGraw-Hill Book Company, Inc., New York, 1955.

The inclusion of minimum profit as an expense is rather unrealistic, especially when it is impossible to designate the exact return which would make a given investment worthwhile. One difficulty with this method is the tendency to use a minimum rate of return equal to that obtained from present investments. This, of course, gives no consideration to the element of risk involved in a new venture. Despite these objections, the use of returns incorporating minimum profits as an expense is acceptable providing the base, or minimum, return and the general method employed are clearly indicated.

Minimum Payout Period. In addition to determining the rate of return on an investment, it is sometimes desirable to find the minimum length of time theoretically necessary before all of the original capital will have been recovered in the form of profits and depreciation charges. This length of time is known as the *minimum payout period.*

Two approaches can be used for determining the minimum payout period. One approach includes a set profit or rate of return as a fictitious expense, but the most commonly used approach considers only the standard expenses. A major objection to the approach including a return rate as an expense is that the rate of return chosen can have an extremely large effect on the final result. However, either of the approaches can be employed as long as the final result includes a statement indicating the method and minimum rate of return used.

Practical Methods for Handling Variations in Annual Profits. If the annual profits obtained from an investment vary from year to year, it is impossible to determine one single rate of return applicable to each year. In many cases, however, the annual variations are not large, and the errors involved in predicting profits are probably greater than the annual changes in income. Therefore, in most economic studies requiring prediction of future profits, the annual profit is assumed to be the same throughout the entire service life as it was in the first year of life. If information shows definitely that a large variation in profits will occur, the most realistic approach is to present the rate of return for each individual year. An alternative approach would be to determine an equivalent, uniform annual return having the same present value as the nonuniform returns.

Example 1. Determination of Rate of Return on Investment and Payout Period (Consideration of Income-tax Effects). A total investment of $1 million is required for a proposed manufacturing plant. It is estimated that the annual income will be $800,000 and the annual expenses will be $520,000 before income taxes. These expenses include $100,000 for depreciation. A minimum annual return of 15 per cent before income taxes is required before the investment will be worthwhile. Income taxes amount to 48 per cent of all pretax profits.

Determine the following:

(*a*) The annual per cent return on the investment before income taxes.

(*b*) The annual per cent return on the investment after income taxes.

(*c*) The annual per cent return on the investment before income taxes based on capital recovery with minimum profit.

(*d*) Standard minimum payout period based on profits after income taxes.

(*e*) Minimum payout period based on profits after income taxes including as an expense a minimum annual return of 7.8 per cent after income taxes.

Solution

(*a*) Annual profit before income taxes = \$800,000 − \$520,000 = \$280,000

$$\text{Annual \% return on investment before income taxes} = \frac{280{,}000}{1{,}000{,}000}(100) = 28\%$$

(*b*) Annual profit after income taxes = (\$280,000)(0.52) = \$145,600

$$\text{Annual \% return on investment after income taxes} = \frac{145{,}600}{1{,}000{,}000}(100) = 14.6\%$$

(*c*) Minimum profit required per year before income taxes = (\$1,000,000)(0.15) = \$150,000

Fictitious expenses based on capital recovery with minimum profit = \$520,000 + \$150,000 = \$670,000 per year

Annual % return on investment before income taxes based on capital recovery with minimum annual rate of return of 15% before income taxes

$$= \frac{(800{,}000 - 670{,}000)(100)}{(1{,}000{,}000)} = 13\%$$

(*d*) Annual profit after income taxes = \$145,600

Annual depreciation charges = \$100,000

Standard minimum payout period based on profits after income taxes

$$= \frac{1{,}000{,}000}{245{,}600} = 4.1 \text{ years}$$

(*e*) Annual profits after income taxes including annual post-tax return of 7.8% as a fictitious expense = 145,000 − (1,000,000)(0.078) = \$67,600

Annual depreciation charges = \$100,000

Minimum payout period based on profits after income taxes including as an expense a minimum annual return of 7.8% after income taxes

$$= \frac{1{,}000{,}000}{167{,}600} = 6.0 \text{ years}$$

NOTE: The method used to solve this problem illustrates the commonly accepted engineering methods for evaluating returns. The time value of money has not been considered.*

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* Investor's method, discounted-cash-flow method, interest-rate-of-return method, present-value method, and the profitability index are used for calculating and reporting returns when it is desirable to take into account the promptness with which money is earned. In all of these methods, the time value of money is considered. They are

Determining Acceptable Returns. It is often possible to make a profit by the investment of capital, but it is not always easy to determine if a given return is sufficient to justify an investment. Many factors must be considered when deciding if a return is acceptable, and it is not possible to give one figure which will apply for all cases.

When dealing with ordinary industrial operations, profits cannot be predicted with absolute accuracy. Risk factors, therefore, must be given careful consideration, and the degree of uncertainty involved in predicted returns on investments plays an important role in determining what returns are acceptable.

A certain amount of risk is involved in any type of investment, but the degree of risk varies widely for different types of enterprises. For example, there is very little uncertainty involved in predicting returns on capital invested in government bonds, and the chances of losing the original capital are very small. However, money invested in a wildcat mining enterprise would stand a good chance of being lost completely with no return whatsoever.

If capital is available for investment in a proposed enterprise, it would also be available for use in other ventures. Therefore, a good basis for determining an acceptable return is to compare the predicted return and the risks involved with returns and risks in other types of investments.

Very conservative investments, such as government bonds, pay low returns in the range of 1½ to 4 per cent, but the risk involved is practically negligible. Preferred stocks yield returns of about 4 to 5½ per cent. There is some risk involved in preferred-stock investments since a business depression or catastrophe could cause reduction in returns or even a loss of the major portion of the capital investment. Common stocks may yield returns as high as 8 or 9 per cent; however, the returns fluctuate considerably with varying economic conditions, and there is always the possibility of losing much or all of the original investment.

It can be stated that moderate risks are involved in common-stock investments. Certainly, at least moderate risks are involved in most industrial projects. In general, a 10 per cent return before income taxes would be the minimum acceptable return for any type of business proposition, even if the economics appeared to be completely sound and reliable. Many industrial concerns demand a predicted pretax return of at least

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based on an average annual return on the invested capital, expressed as a compound interest rate. The average return is equivalent to the maximum interest rate at which the company could borrow funds for investment in the project in order to have the project break even at the end of its expected life. For a simplified treatment of this subject see J. J. Hur, "Chemical Process Economics in Practice," pp. 82–102, Reinhold Publishing Corporation, New York, 1956; or J. B. Weaver and R. J. Reilly, *Chem. Eng. Progr.*, **52**:405 (1956).

25 per cent based on reliable economic estimates before they will consider investing capital in projects that are known to be well engineered and well designed.*†

The final decision as to an acceptable return depends on the probable accuracy of the predicted return and on the amount of risk the investor wishes to take. Availability of capital, personal opinions, and intangible factors, such as the response of the public to changes or appearances, may also have an important effect on the final decision.

ALTERNATIVE INVESTMENTS

In industrial operations, it is often possible to produce equivalent products in different ways Although the physical results may be approximately the same, the capital required and the expenses involved can vary considerably depending on the particular method chosen. Similarly, alternative methods involving varying capital and expenses can often be used to carry out other types of business ventures. It may be necessary, therefore, not only to decide if a given business venture would be profitable, but also to decide which of several possible methods would be the most desirable.

The final decision as to the best among alternative investments is simplified if it is recognized that each dollar of additional investment should yield an adequate rate of return. In practical situations, there are usually a limited number of choices, and the alternatives must be compared on the basis of incremental increases in the necessary capital investment.

The following simple example illustrates the principle of investment comparison. A chemical company is considering adding a new production unit which will require a total investment of $1,200,000 and will yield an annual profit of $240,000. An alternative addition has been proposed requiring an investment of $2 million and yielding an annual profit of $300,000. Although both of these proposals are based on reliable estimates, the company executives feel that other equally sound investments can be made with at least a 14 per cent annual rate of return. Therefore, the minimum rate of return required for the new investment is 14 per cent.

The rate of return on the $1,200,000 unit is 20 per cent, and that for the alternative addition is 15 per cent. Both of these returns exceed the minimum required value, and it might appear that the $2 million investment should be recommended because it yields the greater amount of profit per year. However, a comparison of the incremental investment between the two proposals shows that the extra investment of $800,000 gives a profit of only $60,000, or an incremental return of 7.5 per cent. Therefore, if the company had $2 million to invest, it would be more profitable to accept the $1,200,000 proposal and put the other $800,000 in another investment at the indicated 14 per cent return.

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* For a discussion on acceptable returns in the petroleum industry, see *Chem. Eng.*, **63**(1):132 (1956).

† An analysis by J. Tielrooy, *Chem. Eng. Progr.*, **52**:187 (1956), shows that, in 1954, the average annual return on total assets was 9.5 per cent after taxes for eight major chemical companies.

A general rule for making comparisons of alternative investments can be stated as follows: *The minimum investment which will give the necessary functional results and the required rate of return should always be accepted unless there is a specific reason for accepting an alternative investment requiring more initial capital.* When alternatives are available, therefore, the base plan would be that requiring the minimum acceptable investment. The alternatives should be compared with the base plan, and additional capital would not be invested unless an acceptable incremental return or some other distinct advantage could be shown.

Alternatives When an Investment Must Be Made. The design engineer often encounters situations where it is absolutely necessary to make an investment and the only choice available is among various alternatives. An example of this might be found in the design of a plant requiring an evaporation operation. The evaporator unit must have a given capacity based on the plant requirements, but there are several alternative methods for carrying out the operation. A single-effect evaporator would be satisfactory. However, the operating expenses would be lower if a multiple-effect evaporator were used, because of the reduction in steam consumption. Under these conditions, the best number of effects could be determined by comparing the increased savings with the investment required for each additional effect. A graphical representation showing this kind of investment comparison is presented in Fig. 6-1.

The base plan for an alternative comparison of the type discussed in the preceding paragraph would be the minimum investment which gives the necessary functional results. The alternatives should then be compared with the base plan, and an additional investment would be recommended only if it would give a definite advantage.

When investment comparisons are made, alternatives requiring more initial capital are compared only with lower investments *which have been found to be acceptable.* Consider an example in which an investment of $50,000 will give a desired result, while alternative investments of $60,000 and $70,000 will give the same result with less annual expense. Suppose that comparison between the $60,000 and the $50,000 cases shows the $60,000 investment to be unacceptable. Certainly, there would be no reason to give further consideration to the $60,000 investment, and the next comparison should be between the $70,000 and the $50,000 cases. An illustration of this type of reasoning is included in Example 2.

The design engineer often encounters the situation in which the addition of small investment increments is possible. For example, in the design of a heat exchanger for recovering waste heat, each square foot of additional heat-transfer area can cause a reduction in the amount of heat lost, but the amount of heat recovered per square foot of heat-transfer area decreases as the area is increased. Since the investment for the heat exchanger is a function of the heat-transfer area, a plot of net savings (or net profit due to the heat exchanger) versus total investment can be made. A smooth curve of the type shown in Fig. 6-2 results.

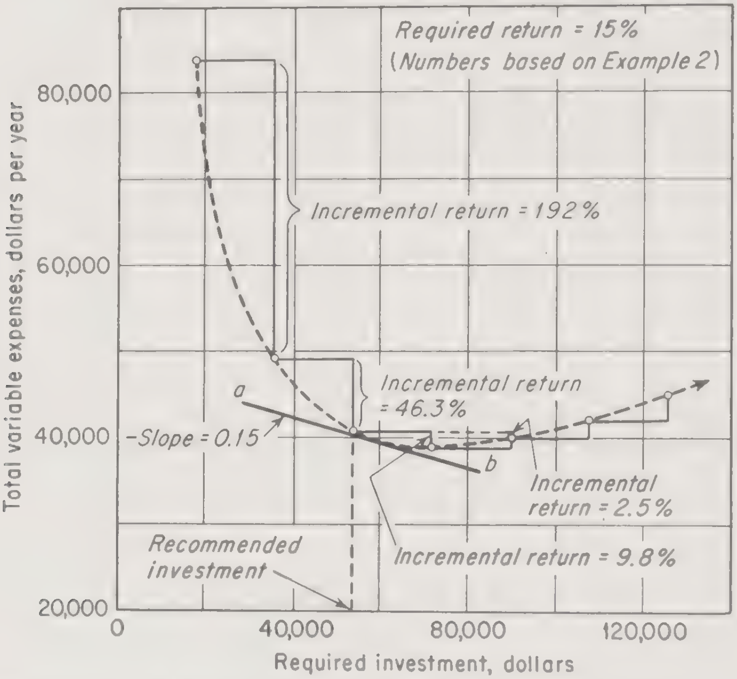

FIG. 6-1. Comparison of alternative investments when one investment must be made for a given service and there are a limited number of choices.

The point of maximum net savings, as indicated by *O* in Fig. 6-2, represents a classical optimum condition. However, the last incremental investment before this maximum point is attained is at essentially a zero per cent return. On the basis of alternative investment comparisons, therefore, some investment less than that for maximum net savings should be recommended.

The exact investment where the incremental return is a given value occurs at the point where the slope of the curve of net savings versus investment equals the required return. Thus, a straight line with a slope equal to the necessary return is tangent to the net-savings-versus-investment curve at the point representing the recommended investment. Such a line for an annual return on incremental investment of 20 per cent is shown in Fig. 6-2, and the recommended investment for this case is indicated by *R*. If an analytical expression relating net savings and investment is available, it is obvious that the recommended investment can be determined directly by merely setting the derivative of the net savings with respect to the investment equal to the required incremental return.

The method described in the preceding paragraph can also be used for continuous curves of the type represented by the dashed curve in Fig. 6-1. Thus, the line *ab* in Fig. 6-1 is tangent to the dashed curve at the point representing the recommended investment for the case of a 15 per cent incremental return.

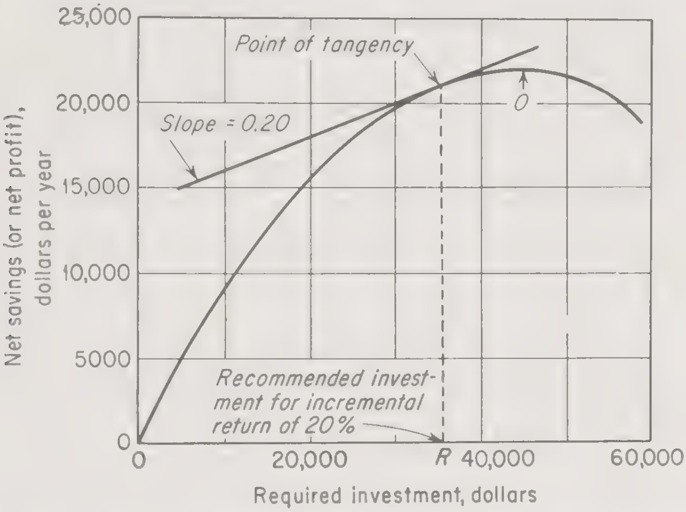

FIG. 6-2. Graphical method for determining investment for a given incremental return when investment increments can approach zero.

Example 2. Investment Comparison for Required Operation with Limited Number of Choices. A plant is being designed in which 150,000 lb per 24-hr day of a water-caustic soda liquor containing 5 per cent by weight caustic soda ,must be concentrated to 40 per cent by weight. A single-effect or multiple-effect evaporator will be used, and a single-effect evaporator of the required capacity requires an initial investment of $18,000. This same investment is required for each additional effect. The service life is estimated to be 10 years, and the salvage value of each effect at the end of the service life is estimated to be $6000. Fixed charges minus depreciation amount to 20 per cent yearly, based on the initial investment. Steam costs $0.60 per 1000 lb, and administration, labor, and miscellaneous costs are $40 per day, no matter how many evaporator effects are used.

Where X is the number of evaporator effects, $0.9X$ equals the number of pounds of water evaporated per pound of steam. There are 300 operating days per year. If the minimum acceptable return on any investment is 15 per cent, how many effects should be used?

Solution

BASIS: 1 operating day

X = total number of evaporator effects

Depreciation per operating day (straight-line method) $= \dfrac{X(18{,}000 - 6000)}{(10)(300)} = \$4.00X$ per day

Fixed charges − depreciation $= \dfrac{X(18{,}000)(0.20)}{300} = \$12.00X$ per day

Pounds of water evaporated per day $= (450{,}000)(0.05)\,(^{95}\!/_{5}) - (450{,}000)(0.05)\,(^{60}\!/_{40})$ $= 393{,}800$ lb/day

Steam costs $= \dfrac{(393{,}800)(0.60)}{X(0.9)(1000)} = \dfrac{\$262.5}{X}$ per day

X = no. of effects	Steam costs per day	Fixed charges minus depreciation per day	Depreciation per day	Labor, etc., per day	Total cost per day
1	\$262.5	\$12	\$ 4	\$40	\$318.5
2	131.3	24	8	40	203.3
3	87.5	36	12	40	175.5
4	65.6	48	16	40	169.6
5	52.5	60	20	40	172.5
6	43.8	72	24	40	179.8

Comparing two effects with one effect,

$$\text{Per cent return} = \frac{(318.5 - 203.3)(300)(100)}{36{,}000 - 18{,}000} = 192\%$$

Therefore, two effects are better than one effect.

Comparing three effects with two effects,

$$\text{Per cent return} = \frac{(203.3 - 175.5)(300)(100)}{54{,}000 - 36{,}000} = 46.3\%$$

Therefore, three effects are better than two effects.

Comparing four effects with three effects,

$$\text{Per cent return} = \frac{(175.5 - 169.6)(300)(100)}{72{,}000 - 54{,}000} = 9.8\%$$

Since a return of at least 15 per cent is required on any investment, three effects are better than four effects, and the four-effect evaporator should receive no further consideration.

Comparing five effects with three effects,

$$\text{Per cent return} = \frac{(175.5 - 172.5)(300)(100)}{90{,}000 - 54{,}000} = 2.5\%$$

Therefore, three effects are better than five effects.

Since the total daily costs continue to increase as the number of effects is increased above five, no further comparisons need to be made.

A three-effect evaporator should be used.

Use of Total Investment and Fixed-capital Investment. A common error made in reporting returns for manufacturing processes is to base all per cent returns on the fixed-capital investment rather than on the total investment. Any time an investment comparison or rate of return is given for complete processes or complete plants, the comparison and rate of return should be based on the total investment, including both working capital and fixed capital. Because the determination of equivalent working-capital investment for single pieces of equipment or for small parts of plants is very difficult, it is usually permissible to neglect working-capital effects in these cases and base the return on the component fixed-capital investment.

Other Methods Occasionally Used for Comparing Alternative Investments. As discussed earlier in this chapter, a minimum required return is sometimes included as a fictitious expense in determining total profits. When this approach is applied correctly to alternative investments, the best investment is the one showing the greatest annual profit. It is important to note that this method does not show the actual returns on each investment or the returns on the incremental investments. Under these conditions, it is particularly necessary to make certain that risk factors are given careful consideration when the minimum required return is selected.

Another method sometimes used for comparing alternative investments and making replacement studies is known as the *capitalized-cost method*.[*] As indicated in Chap. 3 (Interest and Investment Costs), the capitalized cost of equipment is equal to the original cost plus the present value of an indefinite number of renewals. Example 5 in Chap. 3 illustrates the capitalized-cost method for comparing alternative investments when all the investments will yield the same service and there is no difference in operation or maintenance costs. Under these conditions, the investment showing the least capitalized cost would be recommended.

Alternative investments are often capable of giving the same service with different operation or maintenance costs. When this situation exists, the present value of all the variable costs should be included in the capitalized cost. A comparison of this type of alternative investment is illustrated in Example 3.

The capitalized-cost method gives no indication of the return on incremental investments, and this makes final interpretation of the results rather difficult. Inclusion of the present value of a large number of renewals may cause the capitalized cost to be much greater than the capital outlay required for the actual investment. The large amount indicated for the capitalized cost may be very misleading for persons who are not well acquainted with this method. Some estimators who use the capitalized-cost method for comparing alternative investments commonly employ an interest rate equivalent to the cost of borrowed money instead of the minimum acceptable rate of return for the particular investment. This gives a decided bias in favor of the investments requiring the greatest amount of capital.

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[*] See F. C. Jelen, *Chem. Eng.*, **61**(2):199 (1954); **62**(8):181 (1955); **63**(5):165 (1956); **63**(6):247 (1956); *Chem. Eng. Progr.*, **52**:413 (1956). For other methods of comparing alternative investments by including the time value of money, see J. Happel, *Chem. Eng. Progr.*, **51**:533 (1955); J. B. Weaver and R. J. Reilly, *Chem. Eng. Progr.*, **52**:405 (1956).

Despite the objections indicated in the preceding paragraph, the capitalized-cost method is useful for comparing alternative investments. When results based on capitalized costs are presented, it is often advisable to include definitions of terms used in the development. For example, it may be necessary to indicate whether or not the designated capitalized cost includes the present value of all maintenance and operation costs in addition to replacement costs. Risk factors should be considered in setting the interest rate or minimum return used in determining the present value, and a clear indication of this rate should be given along with the final result.

Example 3. Comparison of Alternative Investments Using Standard Method, Minimum-return-as-an-expense Method, and Capitalized-cost Method. A company has three alternative investments which are being considered. Since all three investments are for the same type of unit and yield the same service, only one of the investments can be accepted. The risk factors involved are the same for all three cases, and the company policies dictate a minimum acceptable return of 15 per cent. This may be assumed to mean that other equally sound investments yielding a 15 per cent return are available. Given the following data, determine which investment, if any, should be made by

(*a*) The standard method for comparing alternative investments.
(*b*) The method incorporating minimum return as an expense.
(*c*) The capitalized-cost method.

Investment number	Total capital investment	Salvage value at end of service life	Service life, years	Average annual expenditure for operation, maintenance, taxes, and insurance (expressed as total end-of-year cost)	Profit per year based on all regular expenses
1	$100,000	$ 5,000	10	$45,000	$22,000
2	170,000	9,000	14	31,000	36,000
3	210,000	10,000	16	28,000	40,000

Solution

(*a*) Standard method:

The annual rate of return on the first investment is (22,000/100,000)(100) = 22 per cent.

Since this return is greater than 15 per cent, one of the three investments will be recommended, and it is only necessary to compare the three investments.

Comparing number 2 with number 1,

$$\text{Per cent return} = \frac{36{,}000 - 22{,}000}{170{,}000 - 100{,}000}(100) = 20\%$$

Therefore, investment number 2 is preferred over number 1.

Comparing number 3 with number 2,

$$\text{Per cent return} = \frac{4000}{40{,}000}(100) = 10\%$$

This return is not acceptable, and *the second investment should be recommended.*

(*b*) Comparison method incorporating minimum return as an expense:

Fictitious annual profit with investment number 1 = \$22,000 − (0.15)(\$100,000) = \$7000

Fictitious annual profit with investment number 2 = \$10,500

Fictitious annual profit with investment number 3 = \$8500

The annual profit including a 15 per cent return as an expense is greatest with the second investment; therefore, *the second investment should be recommended.*

(*c*) Capitalized-cost method:

Because the operation, maintenance, and related costs are different for each investment, capitalized cost must be defined as original cost plus present value of an indefinite number of replacements and related variable costs.

From the relationships presented in Chap. 3,

$$\text{Capitalized cost} = \text{original investment} + \frac{\text{replacement cost}}{(1+i)^n - 1} + \frac{\text{annual operating, maintenance, and related costs}}{i}$$

where n = length of service life, years, and i = annual rate of return = 0.15 for this case.

For investment 1,

$$\text{Capitalized cost} = \$100{,}000 + \frac{\$100{,}000 - \$5000}{(1+0.15)^{10} - 1} + \frac{\$45{,}000}{0.15} = \$431{,}000$$

For investment 2,

$$\text{Capitalized cost} = \$170{,}000 + \frac{\$161{,}000}{(1+0.15)^{14} - 1} + \frac{\$31{,}000}{0.15} = \$403{,}000$$

For investment 3,

$$\text{Capitalized cost} = \$210{,}000 + \frac{\$200{,}000}{(1+0.15)^{16} - 1} + \frac{\$28{,}000}{0.15} = \$421{,}000$$

The capitalized cost based on an interest (or minimum return) rate of 15 per cent is least for the second investment.

Therefore, *the second investment should be recommended.*

NOTE. In this example, the profit per year was based on a depreciation cost determined by the sinking-fund method using 15 per cent interest. When this type of sinking-fund depreciation is used, the same investment would be recommended by all three methods as indicated in the solution to the example. Because the capitalized-cost method includes the concept of interest, an investment comparison based on capitalized cost would not necessarily give the same results as the other two methods if depreciation were determined by the common straight-line method.

REPLACEMENTS

Manufacturing concerns and other business establishments are often faced with the problem of whether or not existing equipment or facilities should be replaced. It is convenient to divide the reasons for making replacements into two general types. These are:

1. An existing property *must* be replaced or changed in order to continue operation and meet the required demands for service or production. Some examples of reasons for this type of necessary replacement are:
   a. The property is worn out and can give no further useful service.
   b. The property does not have sufficient capacity to meet the demand placed upon it.
   c. Operation of the property is no longer economically feasible because changes in design or product requirements have caused the property to become obsolete.
2. An existing property is capable of yielding the necessary product or service, but more efficient equipment or property is available which can operate with lower expenses.

When the reason for a replacement falls in the first general type, the only alternatives are to make the necessary changes or else go out of business. Under these conditions, the final economic analysis is usually reduced to a comparison of alternative investments.

The correct decision as to the desirability of replacing an existing property which is capable of yielding the necessary product or service depends on a clear understanding of theoretical replacement policies plus a careful consideration of many practical factors. In order to determine whether or not a change is advisable, the operating expenses with the present equipment must be compared with those that would exist if the change were made. Practical considerations, such as amount of capital available or the benefits to be gained by meeting a competitor's standards, may also have an important effect on the final decision.

Typical Example of Replacement Policy. The following example illustrates the type of economic analysis involved in determining if a replacement should be made: A company is using a piece of equipment which originally cost $30,000. The equipment has been in use for 5 years, and it now has a net realizable value of $6000. At the time of installation, the service life was estimated to be 10 years and the salvage value at the end of the service life was estimated to be zero. Operating costs amount to $22,000 per year. At the present time, the remaining service life of the equipment is estimated to be 3 years.

A proposal has been made to replace the present piece of property by one of more advanced design. The proposed equipment would cost $40,000, and the operating costs would be $15,000 per year. The service life is estimated to be 10 years with a zero salvage value. Each piece of equipment will perform the same service, and all costs other than those for operation and depreciation will remain constant. Depreciation costs are determined by the straight-line method.* The company will not make any unnecessary investments in equipment unless it can obtain an annual return on the necessary capital of at least 10 per cent.

The two alternatives in this example are to continue the use of the present equipment or to make the suggested replacement. In order to choose the better alternative, it is necessary to consider both the reduction in expenses obtainable by making the change and the amount of new capital necessary. The only variable expenses are those for operation and depreciation. Therefore, the annual variable expenses for the proposed equipment would be $15,000 + $40,000/10 = $19,000.

The net realizable value of the existing equipment is $6000. In order to make a fair comparison between the two alternatives, all costs must be based on conditions at the present time. Therefore, the annual depreciation cost for the existing equipment during the remaining three years of service life would be $6000/3 = $2000. For purposes of comparison, the annual variable expenses if the equipment is retained in service would be $22,000 + $2000 = $24,000.

An annual saving of $24,000 − $19,000 = $5000 can be realized by making the replacement. The cost of the new equipment is $40,000, but the sale of the existing property would provide $6000; therefore, it would be necessary to invest only $34,000 to bring about an annual saving of $5000. Since this represents a return greater than 10 per cent, the existing equipment should be replaced.

Book Values and Unamortized Values. In the preceding example, the book value of the existing property was $15,000 at the time of the proposed replacement. However, this fact was given no consideration in determining if the replacement should be made. The book value is based on past conditions, and the correct decision as to the desirability of making a replacement must be based on present conditions.

The difference between the book value and the net realizable value at any time is commonly designated as the *unamortized value*. In the example, the unamortized value was \$15,000 − \$6000 = \$9000. This means that a \$9000 loss was incurred because of incorrect estimation of depreciation allowances.

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* The use of the sinking-fund method for determining depreciation is sometimes advocated for replacement studies. However, for most practical situations, the straight-line method is satisfactory.

Much of the confusion existing in replacement studies is caused by unamortized values. Some people feel that a positive unamortized value represents a loss which would be caused by making a replacement. This is not correct because the loss is a result of past mistakes, and the fact that the error was not apparent until a replacement was considered can have no bearing on the conditions existing at the present time. *When making theoretical replacement studies, unamortized values must be considered as due to past errors, and these values are of no significance in the present decision as to whether or not a replacement should be made.*

Although unamortized values have no part in a replacement study, they must be accounted for in some manner. One method for handling these capital losses or gains is to charge them directly to the profit-and-loss account for the current operating period. When a considerable loss is involved, this method may have an unfavorable and unbalanced effect on the profits for the current period. Many concerns protect themselves against such unfavorable effects by building up a surplus reserve fund to handle unamortized values. This fund is accumulated by setting aside a certain sum each accounting period. When losses due to unamortized values occur, they are charged against the accumulated fund. In this manner, unamortized values can be handled with no serious effects on the periodic profits.

Investment on Which Replacement Comparison Is Based. As indicated in the preceding section, the unamortized value of an existing property is based on past conditions and plays no part in a replacement study. The advisability of making a replacement is usually determined by the rate of return which can be realized from the necessary investment. It is, therefore, important to consider the amount of the investment. *The difference between the total cost of the replacement property and the net realizable value of the existing property equals the necessary investment.* Thus, the correct determination of the investment involves only consideration of the present capital outlay required if the replacement is made.

Net Realizable Value. In replacement studies, the *net realizable value* of an existing property should be assumed to be the market value. Although this may be less than the actual value of the property as far as the owner is concerned, it still represents the amount of capital which can be obtained from the old equipment if the replacement is made. Any attempt to assign an existing property a value greater than the net realizable value tends to favor replacements which are uneconomical.

Analysis of Common Errors Made in Replacement Studies. Most of the errors in replacement studies are caused by failure to realize that a replacement analysis must be based on conditions existing at the present time. Some persons insist on trying to compensate for past mistakes by forcing new ventures to pay off losses incurred in the past. Instead, these losses should be accepted, and the new venture should be considered on its own merit.

Including Unamortized Value as an Addition to the Replacement Investment. This is one of the most common errors. It increases the apparent cost for the replacement and tends to prevent replacements which are really economical. Some persons incorporate this error into the determination of depreciation cost for the replacement equipment, while others include it only in finding the investment on which the rate of return is based. In any case, this method of attempting to account for unamortized values is incorrect. The unamortized value must be considered as a dead loss (or gain) due to incorrect depreciation accounting in the past.

Use of Book Value for Old Equipment in Replacement Studies. This error is caused by refusal to admit that the depreciation accounting methods used in the past were wrong. Persons who make this error attempt to justify their actions by claiming that continued operation of the present equipment would eventually permit complete depreciation. This viewpoint is completely unrealistic because it gives no consideration to the competitive situation existing in modern business. The concern which can operate with good profit and still offer a given product or service at the lowest price can remain in business and force competitors either to reduce their profits or to cease operation.

When book values are used in replacement studies, the apparent costs for the existing equipment are usually greater than they should be, while the apparent capital outlay for the replacement is reduced. Therefore, this error tends to favor replacements which are really uneconomical.

PRACTICAL FACTORS IN ALTERNATIVE-INVESTMENT AND REPLACEMENT STUDIES

The previous discussion has presented the theoretical viewpoint of alternative-investment and replacement studies; however, certain practical considerations also influence the final decision. In many cases, the amount of available capital is limited. From a practical viewpoint, therefore, it may be desirable to accept the smallest investment which will give the necessary service and permit the required return. Although a greater investment might be better on a theoretical basis, the additional return would not be worth the extra risks involved when capital must be borrowed or obtained from some other outside source.

A second practical factor which should be considered is the accuracy of the estimations used in determining the rates of return. A theoretically sound investment might not be accepted because the service life used in determining depreciation costs appears to be too long. All risk factors should be given careful consideration before making any investment, and the risk factors should receive particular attention before accepting an investment greater than that absolutely necessary.

The economic conditions existing at the particular time may have an important practical effect on the final decision. In depression periods or in times when economic conditions are very uncertain, it may be advisable to refrain from investing any more capital than is absolutely necessary.

Many intangible factors enter into the final decision on a proposed investment. Sometimes it may be desirable to impress the general public by the external appearance of a property or by some unnecessary treatment of the final product. These advertising benefits would probably receive no consideration in a theoretical economic analysis, but they certainly would influence management's final decision in choosing the best investment.

Personal whims or prejudices, desire to better a competitor's rate of production or standards, the availability of excess capital, and the urge to expand an existing plant are other practical factors which may be involved in determining whether or not a particular investment will be made.

Theoretical analyses of alternative investments and replacements can be used to obtain a dollars-and-cents indication of what should be done about a proposed investment. The final decision depends on these theoretical results plus practical factors determined by the existing circumstances.

PROBLEMS

1. A proposed chemical plant will require a fixed-capital investment of $10 million. It is estimated that the working capital will amount to 25 per cent of the total investment, and annual depreciation costs are estimated to be 10 per cent of the fixed-capital investment. If the annual profit will be $3 million, determine the standard per cent return on the total investment and the minimum payout period.

2. An investigation of a proposed investment has been made. The following result has been presented to management: The minimum payout period based on capital recovery using a minimum annual return of 10 per cent as a fictitious expense is 10 years; annual depreciation costs amount to 8 per cent of the total investment. Using this information, determine the standard rate of return on the investment.

3. The information given in Prob. 2 applies to conditions before income taxes. If 45 per cent of all profits must be paid out for income taxes, determine the standard rate of return after taxes using the figures given in Prob. 2.

4. A heat exchanger has been designed and insulation is being considered for the unit. The insulation can be obtained in thicknesses of 1, 2, 3, or 4 in. The following data have been determined for the different insulation thicknesses:

	1 in.	2 in.	3 in.	4 in.
Btu/hr saved	300,000	350,000	370,000	380,000
Cost for installed insulation	$1200	$1600	$1800	$1870
Annual fixed charges	10%	10%	10%	10%

What thickness of insulation should be used? The value of heat is 30 cents per 1 million Btu. An annual return of 15 per cent on the fixed-capital investment is required for any capital put into this type of investment. The exchanger operates 300 days per year.

5. A company must purchase one reactor to be used in an over-all operation. Four reactors have been designed, all of which are equally capable of giving the required service. The following data apply to the four designs:

	Design 1	Design 2	Design 3	Design 4
Fixed-capital investment	$10,000	$12,000	$14,000	$16,000
Sum of operating and fixed costs per year (all other costs are constant)	3,000	2,800	2,350	2,100

If the company demands a 15 per cent return on any unnecessary investment, which of the four designs should be accepted?

6. The capitalized cost for a piece of equipment has been found to be $55,000. This cost is based on the original cost plus the present value of an indefinite number of renewals. An annual interest rate of 12 per cent was used in determining the capitalized cost. The salvage value of the equipment at the end of the service life was taken to be zero, and the service life was estimated to be 10 years. Under these conditions, what would be the original cost of the equipment?

7. An existing warehouse is worth $500,000, and the average value of the goods stored in it is $400,000. The annual insurance rate on the warehouse is 1.1 per cent, and the insurance rate on the stored goods is 0.95 per cent. If a proposed sprinkling system is installed in the warehouse, both insurance rates would be reduced to three-quarters of the original rate. The installed sprinkler system would cost $20,000, and the additional annual cost for maintenance, inspection, and taxes would be $300. The required write-off period for the entire investment in the sprinkler system is 20 years. The capital necessary to make the investment is available. The operation of the warehouse is now giving an 8 per cent return on the original investment. Give reasons why you would or would not recommend installing the sprinkler system.

8. A power plant for generating electricity is one part of a plant-design proposal. Two alternative power plants with the necessary capacity have been suggested. One uses a boiler and steam turbine while the other uses a gas turbine. The following information applies to the two proposals:

	Boiler and steam turbine	Gas turbine
Initial investment	$600,000	$400,000
Fuel costs, per year	16,000	23,000
Maintenance and repairs, per year	12,000	15,000
Insurance and taxes, per year	18,000	12,000
Service life, years	20	10
Salvage value at end of service life	0	0

All other costs are the same for either type of power plant. A 12 per cent return is required on any investment. If one of these two power plants must be accepted, which one should be recommended?

9. The facilities of an existing chemical company must be increased if the company is to continue in operation. There are two alternatives. One of the alternatives is to expand the present plant. If this is done, the expansion would cost $130,000. Additional labor costs would be $150,000 per year, while additional costs for overhead, depreciation, taxes, and insurance would be $60,000 per year.

A second alternative requires construction and operation of the new facilities at a location about 50 miles from the present plant. This alternative is attractive because cheaper labor is available at this location. The new facilities would cost $200,000. Labor costs would be $120,000 per year. Overhead costs would be $70,000 per year. Annual insurance and taxes would amount to 2 per cent of the initial cost. All other costs except depreciation would be the same at each location. If the minimum return on any acceptable investment is 9 per cent, determine the minimum service life allowable for the facilities at the distant location for this alternative to meet the required incremental return. The salvage value should be assumed to be zero, and straight-line depreciation accounting may be used.

10. A chemical company is considering replacing a batch wise reactor with a modernized continuous reactor. The old unit cost $40,000 when new 5 years ago, and depreciation has been charged on a straight-line basis using an estimated service life of 15 years and final salvage value of $1000. It is now estimated that the unit has a remaining service life of 10 years and a final salvage value of $1000.

The new unit would cost $70,000 and would cause an increase of $5000 in the gross annual income. It would permit a labor saving of $7000 per year. Additional costs for taxes and insurance would be $1000 per year. The service life is estimated to be 12 years with a final salvage value of $1000. All costs other than those for labor, insurance, taxes, and depreciation may be assumed to be the same for both units. The old unit can now be sold for $5000. If the minimum required return on any investment is 15 per cent, should the replacement be made?

11. The owner of a small antifreeze plant has a small canning unit which cost him $5000 when he purchased it 10 years ago. The unit has been completely depreciated, but the owner estimates that it will still give good service for 5 more years. At the end of 5 years the unit will be worth a junk value of $100. The owner now has an opportunity to buy a more efficient canning unit for $6000 having an estimated service life of 10 years and zero salvage or junk value. This new unit would reduce annual labor and maintenance costs by $1000 and increase annual expenses for taxes and insurance by $100. All other expenses except depreciation would be unchanged. If the old canning unit can be sold for $600, what replacement return on his capital investment will the owner receive if he decides to make the replacement?

CHAPTER 7

COST ESTIMATION

Costs in chemical processes have been discussed in Chap. 2, where a detailed description of the various expenses involved in manufacturing operations is presented. It is now appropriate to consider methods for making estimates of these costs. In general, there are two different types of cost estimates encountered by design engineers: predesign estimates and firm estimates.

Firm estimates are based on complete specifications including all details, such as electrical and piping layouts, architectural design, and instrument specifications. Price quotations for individual pieces of equipment are obtained on the basis of complete blueprints and drawings. A firm estimate should give a result within approximately ±10 per cent of the actual cost. Because of the large amount of detailed work necessary to prepare a firm cost estimate, this step is usually not made until preliminary work has indicated that the new project should be undertaken. Much of the information developed while making a firm estimate can be used as the final specifications for construction and operation of the proposed plant.

Predesign cost estimates require much less detail than firm estimates, but the predesign or preliminary analyses are extremely important for determining if a proposed project should be given further consideration. For this reason, most of the information presented in this chapter is devoted to predesign estimates, although it should be understood that the distinction between predesign and firm estimates gradually disappears as more and more detail is included.

ESTIMATION OF CAPITAL INVESTMENT

Capital investment is defined as the total amount of money needed to supply necessary manufacturing and plant facilities plus the amount of money required for operation of the facilities. Table 1 presents a breakdown showing the various components of total capital investment.

Purchased Equipment. The cost of the purchased equipment is the basis of several predesign methods for estimating capital investment. The determination of equipment cost, therefore, is particularly important. A

TABLE 1. BREAKDOWN OF CAPITAL INVESTMENT

	Cost
Purchased equipment—delivered	$
Complete installation of equipment	
Insulation	
Instrumentation	
Piping	
Electrical installations	
Buildings including services	
Yard improvements	
Service facilities	
Land	
Total physical cost	$
Engineering and construction	
Direct plant cost	$
Contractor's fee	
Contingency	
Fixed-capital investment	$
Working capital [*]	
Total capital investment	$

[*] Working capital is the amount of money which must be available for the normal conduct of business. It includes the following: (1) raw-materials and supplies inventory (estimated to be 1 month's supply); (2) product and in-process inventory (estimated to be total product cost for 1 month of operation); (3) accounts receivable (estimated to be total product cost for 1 month of operation); and (4) available cash (estimated to be amount of money for monthly payment of operating expenses, such as salaries, wages, and raw-material purchases). In ordinary chemical plants, working capital amounts to approximately 10 to 20 per cent of the total capital investment.

complete list of necessary equipment must be drawn up, and the cost of each unit must be determined. In chemical processes, the bulk of the equipment consists of tanks, pumps, heat exchangers, agitators, vessels, and other standard items for which prices are readily available.

The various types of equipment can often be divided conveniently into groups as follows: (1) processing equipment, (2) raw-materials handling and storage equipment, and (3) finished-products handling and storage equipment. The cost of auxiliary equipment and materials, such as insulation and ducts, should also be included. Costs for a large number of different types and capacities of equipment are presented in Chaps. 14 through 17, and the reader is referred to these sections for individual costs.[*]

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[*] Additional references on cost data are presented in the reference list at the end of this chapter.

Six-tenths-factor Rule for Estimating Equipment Cost. It is often necessary to estimate the cost of a piece of equipment when no cost data are available for the particular size or operational capacity involved. If the cost is known for a piece of equipment with a given capacity, the *six-tenths-factor rule* can be used to obtain an estimate of the price for similar equipment having a different capacity. According to this rule, if the cost of a given unit at one capacity is known, the cost of a similar unit with X times the capacity of the first is approximately $(X)^{0.6}$ times the cost of the initial unit.[99] *

$$\text{Cost of equip. } a = \text{cost of equip. } b \left(\frac{\text{capac. equip. } a}{\text{capac. equip. } b}\right)^{0.6}$$

The preceding equation indicates that a log-log plot of capacity versus equipment cost for a given type of equipment should be a straight line with a slope equal to 0.6. Figure 7-1 presents a plot of this sort for shell-and-tube heat exchangers. Many cost data have been correlated in a similar manner, and the agreement with the six-tenths-factor rule is surprisingly good.

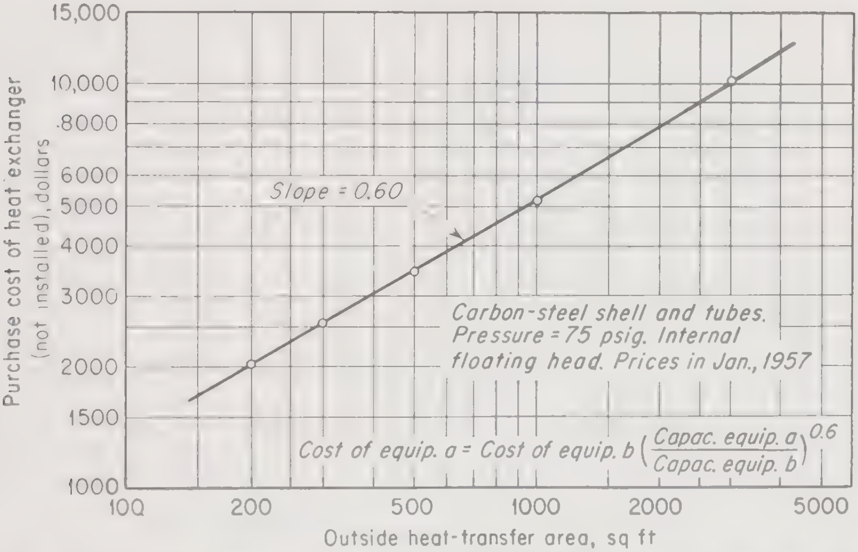

FIG. 7-1. Application of "six-tenths-factor" rule to costs for shell-and-tube heat exchangers. [*J. Happel et al., Estimating Chemical Engineering Costs, Chem. Eng.*, **53**(10):99 (1946); *R. Aries and R. Newton, "Chemical Engineering Cost Estimation," McGraw-Hill Book Company, Inc., New York*, 1955.]

The rule may be applied for estimating both purchased- and installed-equipment costs when additional data are not available. In general, it should not be used beyond a tenfold range of capacity, and care must be taken to make certain the two pieces of equipment are similar with regard to type of construction, materials of construction, temperature and pressure operating range, and other pertinent variables.

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* Superscript numerals are keyed to the References at the end of this chapter.

Installation of Equipment. Equipment installation involves costs for labor, foundations, supports, platforms, site preparation, and other factors directly related to the erection of the equipment. Table 2 presents the general range of installation cost as a percentage of the purchased-equipment cost for various types of equipment.

TABLE 2. INSTALLATION COST FOR EQUIPMENT AS A PERCENTAGE OF THE PURCHASED-EQUIPMENT COST

Type of equipment	*Installation cost, %*
Centrifugal separators	10–35
Compressors	20–60
Dryers	30–60
Evaporators	10–40
Filters	25–45
Heat exchangers	10–35
Mechanical crystallizers	30–50
Metal tanks	20–40
Mixers	10–30
Pumps	10–50
Towers	25–50
Vacuum crystallizers	40–55
Wood tanks	30–60

Analyses of installed costs of equipment in a number of typical chemical plants indicate that the cost of the purchased equipment is approximately 70 per cent of the installed cost.[39] Costs for equipment installation, therefore, are often estimated to be $100/0.70 - 100 = 43$ per cent of the purchased-equipment cost.

Insulation Costs. When very high or very low temperatures are involved, insulation factors can become important, and it may be necessary to estimate insulation costs with a great deal of care. Expenses for equipment insulation and piping insulation are often included under the respective headings of equipment-installation costs and piping costs.

The total cost for the labor and materials required for insulating equipment and piping in ordinary chemical plants is approximately 8 per cent of the purchased-equipment cost. Table 3 gives material and installation-labor expenses for some of the common types of insulation.[2,10]

TABLE 3. INSULATION COSTS

Type of insulation	Cost (1957) per sq ft for	
	Material	Labor
Corkboard:		
1 in.	$0.20	$0.75
2 in.	0.40	0.75
Cork lagging:		
1 in.	0.40	1.10
2 in.	0.60	1.10
Magnesia block:		
1 in.	0.40	1.50
2 in.	0.75	1.60
Mineral-wool blankets:		
1 in.	0.45	1.10
2 in.	0.65	1.10
Mineral-wool blocks:		
1 in.	0.35	1.50
2 in.	0.65	1.60

Instrumentation. Instrument costs, installation-labor costs, and expenses for auxiliary equipment and materials constitute the major portion of the capital investment required for instrumentation. This part of the capital investment is sometimes combined with the general equipment groups. Total instrumentation cost depends on the amount of control required and may amount to 3 to 30 per cent of the purchased cost for all equipment.

Table 4 indicates the purchased costs for different types of instruments. Depending on the complexity of the instruments and the service, additional charges for installation and accessories may amount to 40 to 80 per cent of the purchased cost, with the installation charges being approximately equal to the cost for accessories.[2, 78, 79, 87]

Piping. The cost for piping covers labor, valves, fittings, pipe, supports, and other items involved in the complete erection of all piping used directly in the process. This includes raw-material, intermediate-product, finished-product, steam, water, air, sewer, and other process piping. Detailed information for estimating piping costs is presented in Chap. 14; however, a rough estimate of the capital investment for piping in various types of processes can be obtained from Table 5.[39–41]

TABLE 4. PURCHASED COST OF INSTRUMENTS

Type of instrument	*Cost (1957)*
Temperature:	
Industrial thermometer	$ 30
Recording thermometer	180
Recording-controlling thermometer	430
Indicating pyrometer	200
Recording pyrometer	460
Recording-controlling pyrometer	700
Multipoint recording pyrometer	1000
Flow:	
Displacement meter	220
Indicating manometer	180
Recording manometer	380
Recording-controlling manometer	620
Indicating rotameter (less than 250 gpm)	140
Indicating rotameter (more than 750 gpm)	290
Recording rotameter	430
Recording-controlling rotameter	670
Pressure:	
Indicating	40
Recording	150
Recording-controlling	400
Liquid level:	
Gauge glass	60
Indicating	150
Recording	230
Recording-controlling	480

TABLE 5. PIPING COSTS

Type of process	Per cent of purchased-equipment cost for		
	Material	Labor	Total
Solid	8	6	14
Solid-fluid	21	15	36
Fluid	49	37	86

Electrical Installations. The cost for electrical installations consists primarily of installation labor and materials for power and lighting, with building-service lighting usually included under the heading of building-and-services costs. In ordinary chemical plants, electrical-installations cost amounts to 10 to 15 per cent of the value of all purchased equipment. Table 6 gives approximate costs for standard electrical auxiliaries.[2, 87]

TABLE 6. COST OF ELECTRICAL INSTALLATIONS

Type of industrial installation	*Installed cost (1957)*
Substations and switch gear	$ 40/kva
Inside lighting, standard	50 each
Inside lighting, explosion-proof	120 each
Outside lighting, standard flood	600 each
Overhead feeders	5/ft
Underground feeders	10/ft

Buildings Including Services. The cost for buildings including services consists of expenses for labor, materials, and supplies involved in the erection of all buildings connected with the plant. Costs for plumbing, heating, lighting, ventilating, and similar building services are included. The cost of buildings including services for different types of buildings is shown in Tables 7 and 8.[2, 105] In Table 7, the designation "indoor construction" refers to plants in which most of the operating equipment is located indoors, while "outdoor construction" refers to those plants that have a large portion of the major equipment located outdoors.

TABLE 7. ERECTED COST OF BUILDINGS INCLUDING SERVICES BASED ON EQUIPMENT COST

Purchased-equipment cost	Building-and-services cost, % of purchased-equipment cost	
	Indoor construction	Outdoor construction
Less than $250,000	80	50
$250,000–$1,000,000	65	40
More than $1,000,000	50	30

TABLE 8. ERECTED COST OF BUILDINGS INCLUDING SERVICES

Type of building including services	*Cost (1957) per sq ft of floor area*
Manufacturing, 15-ft floor clearance:	
Steel frame, brick and concrete walls, concrete floors and roof, heating, lighting, plumbing, sprinklers, elevators	$20
Steel frame, walls, and roof, concrete floors, lighting, plumbing, sprinklers	15
Steel frame and roof, concrete floors, open sides, lighting, sprinklers	10
Laboratory:	
Steel frame, brick and concrete walls, concrete floors and roof, heating, lighting, plumbing, sprinklers	20
Laboratory equipment	25
Office:	
Steel frame, brick and concrete walls, concrete floors and roof, heating, lighting, plumbing, sprinklers	20
Office furniture	5
Warehouse, one-story:	
Steel frame, brick and concrete walls, concrete floors and roof, heating, lighting, sprinklers	10
Steel frame, walls, and roof, concrete floors, lighting, sprinklers	5
Type of service	
Electrical lighting, processing building	$ 1.00
Electrical lighting, warehouse	0.50
Heating (excluding boiler)	1.00
Air conditioning	3.00
Sprinklers	0.50

Yard Improvements. Costs for fencing, grading, roads, sidewalks, railroad sidings, landscaping, and similar items constitute the portion of the capital investment included in yard improvements. Yard-improvements cost for chemical plants approximates 10 to 15 per cent of the purchased-equipment cost. The total expense for some typical yard improvements is indicated in Table 9.[2, 55]

TABLE 9. COSTS FOR YARD IMPROVEMENTS

Yard improvement	*Total cost (1957)*
Asphalt pavement	$ 3 per sq yd
Concrete sidewalk	3 per sq yd
Railroad siding	14 per lin ft
Standard chain-link fencing	3 per lin ft

Service Facilities. Utilities for supplying steam, water, power, compressed air, and fuel are part of the service facilities of an industrial plant. Waste disposal, fire protection, and miscellaneous service items, such as shop, first aid, and cafeteria equipment and facilities, require capital investments which are included under the general heading of service-facilities cost.

The total cost for service facilities in chemical plants generally ranges from 20 to 70 per cent of the purchased-equipment cost. Table 10 presents costs for various types of service facilities.[2]

TABLE 10. INSTALLED COSTS OF SERVICE FACILITIES

Type of utility	*Total installed cost (1957)*
Electricity	\$220.00/kva
Steam	6.00/(lb)(hr)
Water, well	0.50/gph
Water, filtered	1.40/gph
Water, softened	2.80/gph
Cooling towers	0.60/gph
Sewage disposal	2.80/gph
Manufactured gas	5.00/cfh
Compressed air	50.00/cfm

Land. The cost for land depends on the location and may vary from less than \$300 per acre in some rural districts to more than \$5000 per acre in highly industrialized areas. As a rough average, land costs for industrial plants amount to 1 to 2 per cent of the total capital investment. Because the value of land usually does not decrease with time, this value should not be included in the capital investment when estimating certain annual operating costs, such as depreciation.

Engineering and Construction. The costs for construction design and engineering, field offices, field supervision, insurance, temporary construction, inspection, and general construction overhead constitute the capital investment for engineering and construction. This cost is ordinarily in the range of 10 to 20 per cent of the total physical cost.[48]

Contractor's Fee. The contractor's fee varies for different situations, but it can be estimated to be about 4 to 10 per cent of the direct plant cost.[48]

Contingencies. A contingency factor is usually included in an estimate of capital investment to compensate for unpredictable events, such as storms, floods, strikes, price changes, small design changes, errors in estimation, and other unforeseen expenses. Contingency factors ranging from 8 to 30 per cent of the direct plant cost are commonly used, with 10 to 20 per cent being considered a fair average value.

Methods for Estimating Capital Investment

Various methods can be employed for estimating capital investment. The choice of any one method depends upon the amount of detailed information available and the accuracy desired. Six methods are outlined in this chapter, with each method requiring progressively less detailed information and less preparation time. Consequently, the degree of accuracy decreases with each succeeding method. A maximum accuracy within approximately ±10 per cent of the actual capital investment can be obtained with method *A*.

Method A. Detailed-item Estimate. A detailed-item estimate requires careful determination of each individual article shown in Table 1. Quotations and detailed estimates of purchased price and installation costs for each piece of equipment or plant facility are used to determine the total physical cost. The balance of the fixed-capital investment, including engineering and construction, contractor's fee, and contingency, is estimated by use of the percentage factors given in the preceding sections. Working capital may be estimated by using the information presented in the footnote accompanying Table 1.

Method B. Item Costs as Percentage of Delivered-equipment Cost. This method for estimating the capital investment requires determination of the delivered-equipment cost. The other items included in the total physical cost are then estimated as percentages of the delivered-equipment cost. The additional components of the capital investment are based on average percentages of the total physical cost, direct plant cost, or total capital investment.

The percentages used in making an estimation of this type should be determined on the basis of the type of process involved, design complexity, required materials of construction, location of the plant, past experience, and other items dependent on the particular unit under consideration. Average values of the various percentages have been determined for typical chemical plants, and these values are presented in Table 11.[19, 39–41]

Method C. Multiplication Factors for Approximation of Capital Investment. The percentages given in Table 11 are rough approximations which hold for the types of plants indicated. These values, therefore, may be combined to give multiplication factors that can be used for estimating the fixed-capital investment, the direct plant cost, the total physical cost, or the total capital investment. Factors for estimating the fixed-capital investment or the total capital investment are given in Table 12. It should be noted that these factors include costs for land and contractor's fees.

Method D. Power Factor Applied to Plant-capacity Ratio. This method is applicable for determining fixed-capital investment, and it requires knowledge of the fixed-capital investment for another plant using the same

TABLE 11. PERCENTAGE FACTORS FOR ESTIMATING CAPITAL-INVESTMENT ITEMS BASED ON DELIVERED-EQUIPMENT COST

The values presented in this table are averages based on estimated and actual costs for major additions to chemical plants at an existing site where the necessary land is available through purchase or present ownership.[*] The values are based on fixed-capital investments ranging from $500,000 to $5,000,000.

Item	Per cent of delivered-equipment cost for		
	Solid-processing plant [†]	Solid-fluid-processing plant [‡]	Fluid-processing plant [§]
Purchased equipment—delivered	100	100	100
Equipment installation (including instrumentation and insulation)	43	43	43
Piping (including insulation)	14	36	86
Electrical installations	15	15	15
Buildings including services	35	35	35
Yard improvements	13	10	10
Service facilities	20	35	50
Land (if purchase is required)	6	6	6
Total physical cost	246	280	345
Engineering and construction	30	40	65
Direct plant cost	276	320	410
Contractor's fee (about 7% of direct plant cost)	19	22	29
Contingency (about 15% of direct plant cost)	41	48	62
Fixed-capital investment	336	390	501
Working capital (about 15% of total capital investment)	60	70	90
Total capital investment	396	460	591

[*] Owing to the extra expense for supplying service facilities, storage facilities, loading terminals, transportation facilities, and other necessary utilities at a completely undeveloped site, the fixed-capital investment for a new plant located at an undeveloped site may be as great as two times the fixed-capital investment for an equivalent plant constructed as an addition to an existing plant.

[†] A coal-briquetting plant would be a typical solid-processing plant.

[‡] A solvent-extraction plant complete with bean-preparation and meal-processing facilities would be a typical solid-fluid-processing plant.

[§] A distillation unit would be a typical fluid-processing plant.

TABLE 12. MULTIPLICATION FACTORS FOR ESTIMATION OF FIXED-CAPITAL INVESTMENT OR TOTAL CAPITAL INVESTMENT

Factor × delivered-equipment cost = fixed-capital investment or total capital investment for major additions to an existing plant.

Type of plant	Factor for	
	Fixed-capital investment	Total capital investment
Solid-processing plant	3.4	4.0
Solid-fluid-processing plant	3.9	4.6
Fluid-processing plant	5.0	5.9

process but having a different production capacity. If a log-log plot of production capacity versus fixed-capital investment is made for one process, the resultant plot will ordinarily be well represented by a straight line. In general, the slopes of these straight lines for various processes average about 0.7.[21, 56] Therefore, the relation between the fixed-capital investments and the production capacities of plants I and II for the same process may be approximated as

$$\text{Fix.-cap. inv. I} = \text{fix.-cap. inv. II}\left(\frac{\text{prod. capac. I}}{\text{prod. capac. II}}\right)^{0.7}$$

If it is necessary to use multiple production units instead of individual units in order to achieve high capacity, the power factor may increase to 0.8 to 1.0. On the other hand, for very small plants or for processes involving extremes of temperature and pressure, the power factor may be as low as 0.3 to 0.5.

Method E. Investment Cost per Unit of Capacity. Many data have been published giving the fixed-capital investment required for various processes per unit of annual production capacity.[4, 37, 70, 71] Although these values depend to some extent on the capacity of the individual plants, it is possible to determine the unit investment costs which apply for average conditions. Average factors of fixed-capital investment per annual ton of production capacity are presented in Table 13. An estimate of the fixed-capital investment for a given process can be obtained by multiplying the appropriate factor by the production capacity of the proposed plant in tons per year.

The values presented in Table 13 are for 1957 price levels. The necessary correction for change of costs with time can be made by use of cost indexes, as discussed later in this chapter.

Table 13. Fixed-capital Investment per Annual Ton of Capacity and Turnover Ratios for Various Chemical Plants

$$\text{Unit investment cost} = \frac{\text{\$ fixed-capital investment}}{\text{annual ton of production capacity}}$$

$$\text{Turnover ratio} = \frac{\text{sales value of product as \$/year}}{\text{\$ fixed-capital investment}}$$

Type of plant	Unit investment cost (1957)	Turnover ratio
Acetaldehyde from acetylene	54	4.2
Acetic acid from acetaldehyde	50	3.8
Acetic acid from alcohol oxidation	270	0.7
Acetic anhydride from acetic acid	200	1.4
Acetylene from calcium carbide	230	1.1
Alumina from bauxite	100	0.8
Ammonia, synthetic	250	0.4
Ammonium sulfate	8	5.6
Aniline from nitrobenzene	320	1.2
Butadiene from butane	1200	0.2
Butanol, synthetic	580	0.6
Calcium carbide	87	1.6
Cement, portland	21	1.0
Chlorine and caustic, electrolytic	290	0.5
Ethanol from grain	160	1.0
Ethanol from molasses	85	1.8
Ethylene dichloride	400	0.5
Ethylene glycol	310	1.1
Formaldehyde, 37%, from hydrocarbons	170	0.5
Formaldehyde, 37%, from methanol	18	4.2
Furfural	310	0.7
Glycerine, synthetic	620	1.0
Hydrochloric acid from salt	170	0.4
Hydrofluoric acid	210	2.0
Lime	6	1.8
Methanol, synthetic	270	0.4
Nitric acid, synthetic	170	1.3
Paper, Kraft or newsprint, from pulp	150	0.8
Pentaerythritol	480	1.4
Phenol, synthetic	450	0.8
Phosphoric acid, blast furnace	180	0.7
Phosphoric acid, Dorr process	61	2.0
Soda ash	70	0.4
Styrene	600	0.6
Sulfuric acid, contact, from pyrites	40	0.6
Sulfuric acid, contact, from sulfur	19	1.2
Urea	49	2.3

Method F. Turnover Ratios. Turnover ratio is defined as the dollars of annual sales value per dollar of fixed-capital investment. Table 13 presents average values of turnover ratios for a number of different processes. The annual sales value of the products from a proposed plant divided by the appropriate turnover ratio gives a rough estimate of the necessary fixed-capital investment.

$$\text{Fix.-cap. inv.} = \frac{\text{sales value of products as \$/year}}{\text{turnover ratio}}$$

$$\begin{aligned}\text{Sales value of products as \$/year} &= \text{production capacity as tons/year} \\ &\quad \times \text{selling price of products as \$/ton}\end{aligned}$$

The reciprocal of turnover ratio is sometimes defined as *capital ratio.*

A general rule of thumb for estimating fixed-capital investment is based on the assumption that the turnover ratio is 1.0. With this assumption, one dollar of fixed-capital investment is required for each dollar of annual sales value.

COST INDEXES

When a firm cost estimate is made, it is necessary to obtain quotations from manufacturers in order to know the exact cost for a given article at the present time. For predesign estimates, however, it is seldom advisable to obtain an accurate quoted price from an outside source. Instead, available cost data are usually employed. If these data are treated correctly, an accurate estimate based on existing conditions can be obtained.

Most cost data which are available for immediate use in a preliminary or predesign estimate are based on conditions at some time in the past. Because prices may change considerably with time, some method must be used for converting costs applicable at a past date to equivalent costs that are essentially correct at the present time. This can be done by the use of cost indexes.

A cost index is merely a number for a given year showing the cost at that time relative to a certain base year. If the cost at some time in the past is known, the equivalent cost at the present time can be determined by multiplying the original cost times the ratio of the present index value to the index value applicable when the original cost was obtained.

$$\text{Present cost} = \text{original cost}\left(\frac{\text{index value at present time}}{\begin{array}{c}\text{index value at time original}\\ \text{cost was obtained}\end{array}}\right)$$

Cost indexes can be used to give a general estimate, but no index can take into account all factors, such as special technological advancements or local conditions. The common indexes permit fairly accurate estimates if the time period involved is less than 10 years.

Many different types of cost indexes are published regularly.[*] Some of these can be used for estimating equipment costs; others apply specifically to labor, construction, materials, or other specialized fields. The most common of these indexes are the *Marshall and Stevens All-industry and Process-industry Equipment Indexes*, the *Engineering News-Record Construction Index*, the *Nelson Refinery Construction Index*, and *Labor and Material Indexes* published by the U.S. Bureau of Labor. Table 14 presents a list of the values for various types of indexes.

TABLE 14. COST INDEXES

Year	Marshall and Stevens installed-equipment indexes 1926 = 100		*Eng. News-Record* construction index			Nelson refinery construction-in-petroleum-industry index 1946 = 100
	All-industry	Process-industry	1913 = 100	1926 = 100	1949 = 100	
1945	103	104	308	148	65	90
1946	123	123	346	166	73	100
1947	151	149	413	199	87	117
1948	163	162	461	222	97	133
1949	161	162	477	229	100	140
1950	168	167	510	245	107	146
1951	180	178	543	261	114	157
1952	181	179	569	274	119	164
1953	183	181	600	288	126	174
1954	185	184	628	302	132	180
1955	191	189	660	317	138	184
1956	209	206	690	332	145	195
1957 (Jan.)	219	217	709	341	149	202

Marshall and Stevens Equipment-cost Indexes.[†] The Marshall and Stevens equipment indexes are divided into two categories. The all-industry equipment index is simply the arithmetic average of the individual indexes for 47 different types of industrial, commercial, and housing equipment. The process-industry equipment index is a weighted average of eight of these, with the weighting based on the total product value of the various process industries. The percentages used for the weighting in a typical year are as follows: cement, 2; chemicals, 48; clay products, 2; glass, 3; paint, 5; paper, 10; petroleum, 22; and rubber, 8.

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[*] For a detailed summary of various cost indexes, see *Eng. News-Record*, vol. 57, no. 23, Dec. 6, 1956.

[†] Values for the Marshall and Stevens equipment-cost indexes are published periodically in *Chemical Engineering*. For a complete description of these indexes, see R. W. Stevens, *Chem. Eng.*, **54**(11):124 (1947).

The Marshall and Stevens indexes are based on an index value of 100 for the year 1926. These indexes take into consideration the cost of machinery and major equipment plus costs for installation, fixtures, tools, office furniture, and other minor equipment.

Engineering News-Record* Construction Cost Index. Relative construction costs at various dates can be estimated by use of the *Engineering News-Record* construction index. This index shows the variation in labor rates and materials costs for industrial construction. It employs a composite cost for 2500 lb of structural steel, 1088 fbm of lumber, 6 bbl of cement, and 200 hr of common labor. The index is usually reported on one of three bases: an index value of 100 in 1913, 100 in 1926, or 100 in 1949.

Nelson Refinery Construction Cost Index.† Construction costs in the petroleum industry are the basis of the Nelson refinery construction index. The total index percentages are weighted as follows: skilled labor, 30; common labor, 30; iron and steel, 24; building materials, 8; and miscellaneous equipment, 8. An index value of 100 is used for the base year of 1946.

Materials-and-Labor Cost Indexes. The U.S. Department of Labor publishes monthly statistics giving materials and labor indexes for various industries.‡ The data presented in Fig. 7-2 apply for the manufacture of process equipment. The labor index is reported as the average earnings in cents per hour for workers involved in the manufacture of durable goods. This compares with an average wage of approximately 100 cents per hour in 1926. The material index is based on an index value of 100 in 1926 and applies to the metals and metal-products industries.§

By obtaining a total labor-and-material index, the values given in Fig. 7-2 can be used to estimate the present cost of purchased equipment from the cost of similar equipment at a past date.[10] For process equipment made

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* The *Engineering News-Record* construction index appears weekly in the *Engineering News-Record*. For a complete description of this index and the revised basis, see *Eng. News-Record*, **143**(9):398 (1949).

† The Nelson refinery construction index is published the first week of each month in the *Oil and Gas Journal*. For a complete description of this index, see *Oil Gas J.*, **48**(32):91 (1949); **51**(9):105 (1952).

‡ *Monthly Labor Review*, U.S. Bureau of Labor Statistics.

§ In 1952, the materials index was revised to a basis of 100 for the average years of 1947 to 1949. However, for estimating purchased-equipment costs, the 1926 basis of 100 is convenient. To convert to the basis of 1926 = 100, multiply the index value based on 1947 to 1949 = 100 by 1.58 (June, 1950, conversion factor). For details on the revised basis, see *Monthly Labor Review*, **74**(2):180 (1952).

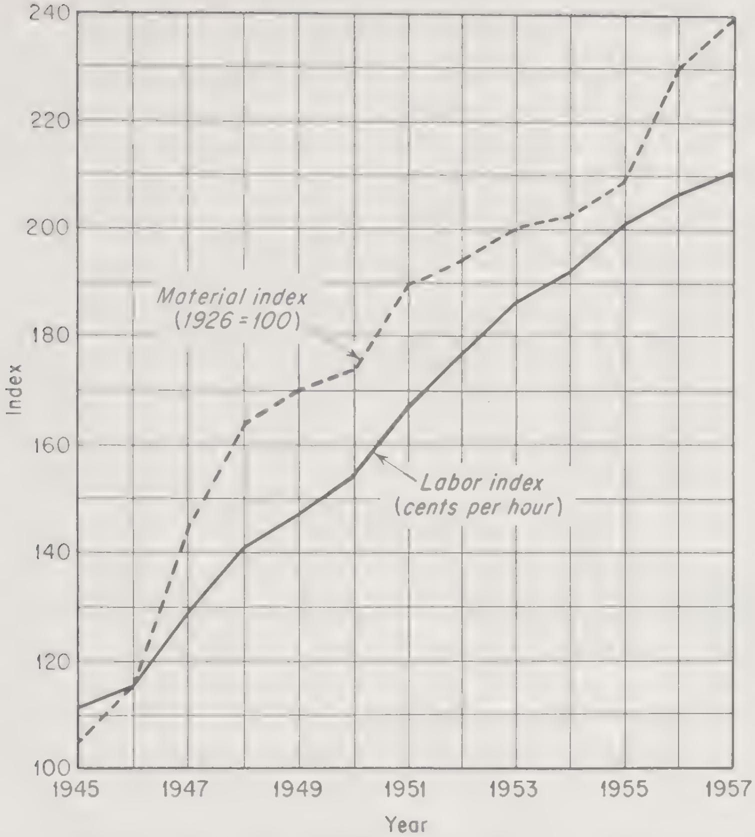

FIG. 7-2. Material and labor indexes for manufacture of process equipment.

of ordinary materials of construction, labor may be assumed as accounting for 50 per cent of the total index, while materials account for the other 50 per cent. If special materials of construction are used, 35 per cent of the total index can be attributed to labor and 65 per cent to materials.

The total labor-and-material index equals the sum of the fractional amount of each item times the value of its index. For example, in January, 1949, the material index was 170 and the labor index was 147. In January, 1953, the material index was 200 and the labor index was 187. For the case of an evaporator made from ordinary materials of construction, the total index in January, 1949, was $(170)(0.5) + (147)(0.5) = 158.5$. In January, 1953, the total index was $(200)(0.5) + (187)(0.5) = 193.5$. The ratio of the two total indexes at two different times may be used to make cost estimates. If the purchased cost of an evaporator was \$10,000 in January, 1949, an equivalent evaporator should have had a purchased cost of approximately $(\$10{,}000)(193.5/158.5) = \$12{,}200$ in January, 1953.

ESTIMATION OF TOTAL PRODUCT COST

Methods for estimating the total capital investment required for a given plant are presented in the first part of this chapter. Determination of the necessary capital investment is only one part of a complete cost estimate. Another equally important part is the estimation of costs for operating the plant and selling the products. These costs can be grouped under the general heading of *total product cost.*

A breakdown showing the individual components of total product cost is presented in Table 15. The amount of each of these component costs must be estimated separately to obtain a firm estimate. Preliminary estimates, however, are often based partially on approximate percentages or factors that are applicable to the particular plant or process under consideration. The percentages indicated in Table 15 give the ranges encountered in typical chemical plants. Because of the wide variations in different types of plants, the factors presented in Table 15 should be used only when more accurate data are not available.

A detailed description of the various components of total product cost is presented in Chap. 2 (Costs in Chemical Processes). Tables 16 through 21 give information on costs for raw materials, operating labor, utilities, and maintenance. The information presented in these tables can be used for making preliminary or predesign estimates of total product cost.

TABLE 15. ESTIMATION OF TOTAL PRODUCT COST (SHOWING INDIVIDUAL COMPONENTS)

The percentages indicated in the following summary of the various costs involved in the complete operation of manufacturing plants are approximations applicable to ordinary chemical processing plants. It should be realized that the values given can vary depending on many factors, such as plant location, type of process, and company policies. Percentages are expressed on a yearly basis.

I. **Factory manufacturing cost** = direct production costs + fixed charges + plant-overhead costs
  - *A*. Direct production costs (about 60% of total product cost)
    1. Raw materials (20±% of total product cost)
    2. Operating labor (5–20% of total product cost)
    3. Direct supervisory and clerical labor (10–20% of operating labor)
    4. Maintenance and repairs (2–10% of fixed-capital investment)
    5. Operating supplies (10–20% of cost for maintenance and repairs)
    6. Utilities (10–20% of total product cost)
    7. Patents and royalties (0–6% of total product cost)
  - *B*. Fixed charges (10–20% of total product cost)
    1. Depreciation (depends on life period, salvage value, and method of calculation—about 10% of fixed-capital investment for machinery and equipment and 2–3% of building value for buildings)
    2. Local taxes (1–4% of fixed-capital investment)
    3. Insurance (0.4–1% of fixed-capital investment)
    4. Rent (8–10% of value of rented land and buildings)

TABLE 15. ESTIMATION OF TOTAL PRODUCT COST (SHOWING INDIVIDUAL COMPONENTS) (*Continued*)

    C. Plant-overhead costs (50–70% of cost for operating labor, supervision, and maintenance, or 5–15% of total product cost); includes costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities

II. **General expenses** = administrative costs + distribution and selling costs + research and development costs

    A. Administrative costs (about 15% of costs for operating labor, supervision, and maintenance, or 2–5% of total product cost); includes costs for executive salaries, clerical wages, legal fees, office supplies, and communications

    B. Distribution and selling costs (2–20% of total product cost); includes costs for sales offices, salesmen, shipping, and advertising

    C. Research and development costs (2–5% of every sales dollar or about 5% of total product cost)

    D. Financing (interest) * (0–6% of total capital investment)

III. **Total product cost** † = factory manufacturing cost + general expenses

IV. **Gross-earnings cost** (gross earnings = total income − total product cost; amount of gross-earnings cost depends on amount of gross earnings for entire company and income-tax regulations; a general range for gross-earnings cost is 30–60% of gross earnings)

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* Interest on borrowed money is often considered as a fixed charge.

† If desired, a contingency factor can be included by increasing the total product cost by 1–5%.

TABLE 16. PRICE OF RAW MATERIALS

Cost of raw materials = purchased price and delivery expense for all materials consumed in the manufacturing operation + amortized cost of catalytic materials.

Current cost data for chemicals are available in *Chemical and Engineering News* (quarterly); *Oil, Paint, and Drug Reporter;* and other regular publications.

Following are price trends for six basic chemicals. (Upper line of figures indicates high for year cited; lower line indicates low for year cited.)

Chemical	1950	1951	1952	1953	1954	1955	1956
Sulfuric acid, 66°, tanks, ton.......	$19.85	$20.00	$20.00	$22.35	$22.35	$22.35	$22.35
	17.00	19.85	20.00	19.61	22.35	22.35	22.35
Caustic soda, 76% solid, c.l., cwt...	3.35	3.35	3.35	3.70	3.85	3.85	4.30
	3.05	3.35	3.35	3.35	3.70	3.85	4.10
Benzene, 90%, tanks, gal..........	0.37	0.37	0.38¾	0.40	0.42	0.36	0.36
	0.22	0.30	0.30	0.30	0.40	0.36	0.36
Glycerol, USP, c.l., lb............	0.58	0.54¼	0.44¼	0.44	0.33	0.29	0.31½
	0.24¼	0.54¼	0.34	0.33	0.29	0.29	0.27⅞
Ethanol, synthetic, tanks, gal......	0.32	0.40	0.40	0.40	0.40	0.40	0.47
	0.26	0.40	0.40	0.40	0.40	0.40	0.42
Acetic acid, glacial, tanks, cwt.....	9.00	9.00	9.00	9.00	10.00	10.00	10.50
	7.50	9.00	9.00	9.00	9.00	10.00	10.00

TABLE 17. ABBREVIATIONS AND TERMS USED IN REPORTING PRICE OF CHEMICALS *

anhyd.	anhydrous
bbl.	barrel
bot.	bottle
case	fiber or wooden box with specified number of bags, canisters, cans, or bottles
cby.	carboys
c.i.f.	cost, insurance, and freight, as in quotations of foreign seller
c.l.	carlots or carloads
clr.	color
cnstr.	canister
cntr.	container
coml.	commercial grade
conc.	concentrated
CP	chemically pure
cryst.	crystals
cts.	cents
cu. ft.	cubic feet
cwt.	hundredweight or hundredweights, usually 100 lbs.
cyl.	steel cylinder
dely.	delivery
denat.	denatured
dist.	distilled
DL	dextro laevo
dlr.	dealer or dealers
dlvd.	delivered
f.a.s.	free alongside ship, as in quotations for export
fert.	fertilizer grade
fib.	fiber
f.o.b.	free on board
form.	formulator
fort.	fortified
frt.	freight
frt. alld.	freight cost allowed by seller
frt. eqld.	freight cost equalized to meet competition
gal.	gallon
gen.	general
gran.	granular
imp.	imported
incl.	included
indust.	industrial grade
kgs.	kegs
kilo	kilogram or 1000 grams
l.c.l.	less than carloads
liq.	liquid
l.t.l.	less than truckloads
long ton	2240 pounds
med.	medium
met.	metallurgical grade
metric ton	1000 kilograms or 2204.6 pounds
mg.	milligram
min.	minimum
nat.	natural
NF	National Formulary conformance
NNR	new and nonofficial remedies
non-ret.	nonreturnable
oz.	ounce
pharm.	pharmaceutical grade
pkg.	package
powd.	powder
pulv.	pulverized
purif.	purified
quant.	quantity
rect.	rectified
ref.	refined
same basis	delivery or package specifications same as those in preceding quotation
short ton	2000 pounds
soln.	solution, or in solution
spl.	special
s.s.	stainless steel
std.	standard
synth.	synthetic
tanks	tank cars or tank trucks
tech.	technical grade, usually the grade for industrial use as distinguished from a chemical reagent or product of higher purity
t.l.	truckload
ton	short ton unless otherwise defined
transp.	transportation
USP	U.S. Pharmacopeia conformance
visc.	viscosity
whse.	warehouse or nearest warehouse point of the seller
wks.	at the works, corresponding to f.o.b. plant
zone	specified sales area; price differences between zones for a given chemical vary with freight and other costs
*	nominal
†	freight allowed
‡	freight equalized

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* *Chemical and Engineering News.*

TABLE 18. OPERATING LABOR, POWER, STEAM, AND WATER REQUIREMENTS FOR VARIOUS PROCESSES [108, 123, 124]

Process	Operating labor as man-hours per ton of product	Consumption of		
		Electrical energy as kwhr per lb of product	Steam as lb per lb of product	Water as gal per lb of product
Acetic acid from carbide	29	0.21	3.1	43
Alumina from bauxite	3.7	0.090	7.0	3.2
Aluminum	16	9.0		
Aluminum sulfate	1.5	0.015	3.4	0.5
Calcium carbide	3.0	1.7	....	16
Cement, portland	2.1	0.050	....	0.4
Ethanol from molasses	3.1	0.017	6.1	8.0
Ethylene glycol, chlorohydrin	9.0	0.080	12	40
Gasoline, catalytic	0.2	0.001	0.1	1.2
Gasoline, natural	1.5	.....	....	3.6
Gasoline, polymer	0.5	0.001	0.5	6.0
Hydrochloric acid from salt	5.2	0.043	....	1.5
Hydrochloric acid, synthetic	3.2	0.002	....	0.4
Lactose	24	0.17	40	100
Magnesium, electrolytic	27	8.0		
Nitric acid from ammonia	1.0	0.19	0.3	7.3
Oxygen, liquid, small scale	48	0.93	....	21
Oxygen, 95%, large scale	0.2	0.22	2.2	13
Phenol by sulfonation	8.5	0.12	2.0	
Phosphoric acid, blast furnace	3.0	0.002	....	37
Phosphoric acid, Dorr process	1.7	0.052	0.8	7.3
Phosphoric acid, electric furnace	0.8	1.9		
Soda ash, ammonium-soda process	3.5	0.048	2.0	8.0
Sodium hydroxide and chlorine, salt electrolysis	9.5	0.75		
Sodium hydroxide, lime-soda process	0.9	0.044	1.4	1.1
Sodium metal	13	4.9	5.1	37
Sulfur dioxide, liquid	10	0.002	3.3	9.0
Sulfuric acid, contact	0.6	0.015	0.1	2.2

TABLE 19. TYPICAL LABOR REQUIREMENTS FOR PROCESS EQUIPMENT[2,5,10]

Type of equipment	*Men per unit*
Dryer, rotary	½
Dryer, spray	1
Dryer, tray	½
Centrifugal separator	¼–½
Crystallizer, mechanical	⅙
Filter, vacuum	⅛–¼
Evaporator	¼
Reactor, batch	1
Reactor, continuous	½
Steam plant (100,000 lb/hr)	3

TABLE 20. RATES FOR VARIOUS INDUSTRIAL UTILITIES

Utility	*Cost (1957)*
Steam:	
500 psig	\$0.50–\$1.00/1000 lb
100 psig	0.25–0.70/1000 lb
Exhaust	0.15–0.30/1000 lb
Electricity:	
Purchased	0.008–0.02/kwhr
Self-generated	0.004–0.01/kwhr
Cooling water:	
Well	0.02–0.10/1000 gal
River or salt	0.01–0.05/1000 gal
Tower	0.01–0.06/1000 gal
Process water:	
City	0.07–0.25/1000 gal
Filtered and softened	0.10–0.35/1000 gal
Distilled	0.60–1.00/1000 gal
Compressed air:	
Process air	0.015–0.05/1000 cu ft (at SC) *
Filtered and dried for instruments	0.04–0.10/1000 cu ft (at SC) *
Natural gas	0.20–0.80/1000 cu ft (at SC) *
Manufactured gas	0.40–1.30/1000 cu ft (at SC) *
Fuel oil	0.04–0.12/gal
Coal	6.00–12.00/ton
Refrigeration (ammonia), to 34°F	0.50/ton-day (288,000 Btu removed)

* For these cases, standard conditions are designated as a pressure of 29.92 in. Hg and a temperature of 60°F.

TABLE 21. ESTIMATION OF COSTS FOR MAINTENANCE AND REPAIRS[2,5]

Type of operation	Maintenance cost as percentage of fixed-capital investment (on yearly basis)		
	Wages	Materials	Total
Simple chemical processes	1–3	1–3	2–6
Average processes with some corrosion problems	2–4	3–5	5–9
Complicated processes, severe use such as high pressure or high temperature	3–5	4–6	7–11

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PROBLEMS

1. An installed heat exchanger with 500 sq ft of heating area cost $3000 in 1948. Estimate the installed cost in 1954 for a similar heat exchanger with 1200 sq ft of heating area.

2. The purchased cost of a 1400-gal steel tank is $1800. The tank is cylindrical with flat top and bottom, and the diameter is 6 ft. If the entire outer surface of the tank is to be covered with 2 in. of cork lagging, estimate the total cost for the installed and insulated tank.

3. A one-story warehouse 120 by 60 ft is to be added to an existing plant. An asphalt-pavement service area 60 by 30 ft will be added adjacent to the warehouse. It will also be necessary to put in 500 lin ft of railroad siding to service the warehouse. Utility service lines are already available at the warehouse site. The proposed warehouse has a concrete floor and steel frame, walls, and roof. No heat is necessary, but lighting and sprinklers must be installed. Estimate the total cost of the proposed addition.

4. The purchased cost of equipment for a solid-processing plant is $500,000. The plant is to be constructed as an addition to an existing plant. Estimate the total capital investment and the fixed-capital investment for the plant. What percentage of the fixed-capital investment is due to cost for land and contractor's fee?

5. Estimate the fixed-capital investment required for a formaldehyde plant which has a capacity of 100,000 lb of 37 per cent formaldehyde per day. The methanol-oxidation process is used and the plant may be considered to be operating full time.

6. The total capital investment for a chemical plant is $1 million, and the working capital is $100,000. If the plant can produce an average of 8000 lb of final product per day during a 365-day year, what selling price in dollars per pound of product would be necessary to give a turnover ratio of 1.0?

7. The purchased cost for a stainless-steel reactor was $25,000 in 1950. Estimate the purchased cost for an equivalent reactor at the present time by using labor and material indexes and considering stainless steel as a special material of construction. Compare this result with that obtained by assuming the installation factor as constant and using the Marshall and Stevens index.

8. The purchased-equipment cost for a plant which produces pentaerythritol (solid-fluid-processing plant) is $300,000. The plant is to be an addition to an existing formaldehyde plant. The major part of the building cost will be for indoor construction, and the contractor's fee will be 10 per cent of the direct plant cost. All other costs are close to the average values found for typical chemical plants. On the basis of this information, estimate the following:

(*a*) The total physical cost.
(*b*) The direct plant cost.
(*c*) The fixed-capital investment.
(*d*) The total capital investment.

9. A cost estimate is being prepared for a new plant, and one portion of the project requires estimation of the costs for the installations necessary to supply steam, cooling-tower water, and electricity. The process requires 14,000 lb per hour of 100-psig steam, 10,000 gph of cooling-tower water, and 500 kva of electricity. Estimate the installed cost for these utilities.

10. Estimate the total operating cost per day for labor, power, steam, and water in a plant producing 100 tons of nitric acid per day from ammonia. Use average costs for utilities. Consider all water as city water. The steam pressure may be assumed to be 100 psig. Labor rates average $2.00 per man-hour. Electricity must be purchased.

11. The total capital investment for a conventional chemical plant is $1,500,000, and the plant produces 3 million lb of product annually. The selling price of the product is $0.41 per pound. Working capital amounts to 15 per cent of the total capital investment. The investment is from the company funds, and no interest is charged. Raw-materials costs for the product are $0.045 per pound, labor $0.04 per pound, utilities $0.025 per pound, and packaging $0.004 per pound. Distribution costs are 5 per cent of the total product cost. Estimate the following:

(*a*) Factory manufacturing cost per pound of product.
(*b*) Total product cost per year.
(*c*) Profit per pound of product before taxes.
(*d*) Annual per cent return on total investment before taxes.

12. Estimate the factory manufacturing cost per 100 lb of product under the following conditions:

Fixed-capital investment = $2 million
Annual production output = 10 million lb of product
Raw-materials costs = $0.12/lb of product
Utilities
  100 psig steam = 50 lb/lb of product
  Purchased electrical power = 0.4 kwhr/lb of product
  Filtered and softened water = 10 gal/lb of product
Operating labor = 20 men per shift at $2.00 per man-hour
Plant operates three hundred 24-hr days per year
Corrosive liquids are involved
Shipments are in bulk carload lots
A large amount of direct supervision is required
There are no patent, royalty, interest, or rent charges
Plant-overhead costs amount to 50 per cent of the cost for operating labor, supervision, and maintenance

CHAPTER 8

COST AND ASSET ACCOUNTING

The design engineer, by analyses of costs and profits, attempts to predict whether capital should be invested in a particular project. After the investment is made, records must be maintained to check on the actual financial results. These records are kept and interpreted by accountants. The design engineer, of course, hopes his predictions will agree with the facts reported by the accountant. There is little chance for agreement, however, if both parties do not consider the same cost factors, and comparison of the results is simplified if the same terminology is used by the engineer and the accountant.

The purpose of accounting is to record and analyze any financial transactions that have an influence on the utility of capital. Accounts of expenses, income, assets, liabilities, and similar items are maintained. These records can be of considerable value to the engineer, since they indicate where errors were made in past estimates and give information that can be used in future evaluations. Thus, the reason why the design engineer should be acquainted with accounting procedures is obvious. Although it is not necessary to know all the details involved in accounting, a knowledge of the basic principles as applied in economic evaluations is an invaluable aid to the engineer.

This chapter presents a survey of the accounting procedures usually encountered in industrial operations. Its purpose is to give an understanding of the terminology, basic methods, and manner of recording and presenting information as employed by industrial accountants.

OUTLINE OF ACCOUNTING PROCEDURE

The diagram in Fig. 8-1 shows the standard accounting procedure, starting with the recording of the original business transactions and proceeding to the final preparation of summarizing balance sheets and income statements. As the day-by-day business transactions occur, they are recorded in the *journal*. A single journal may be used for all entries in small businesses, but large concerns ordinarily use several types of journals, such as cash, sales, purchase, and general journals.

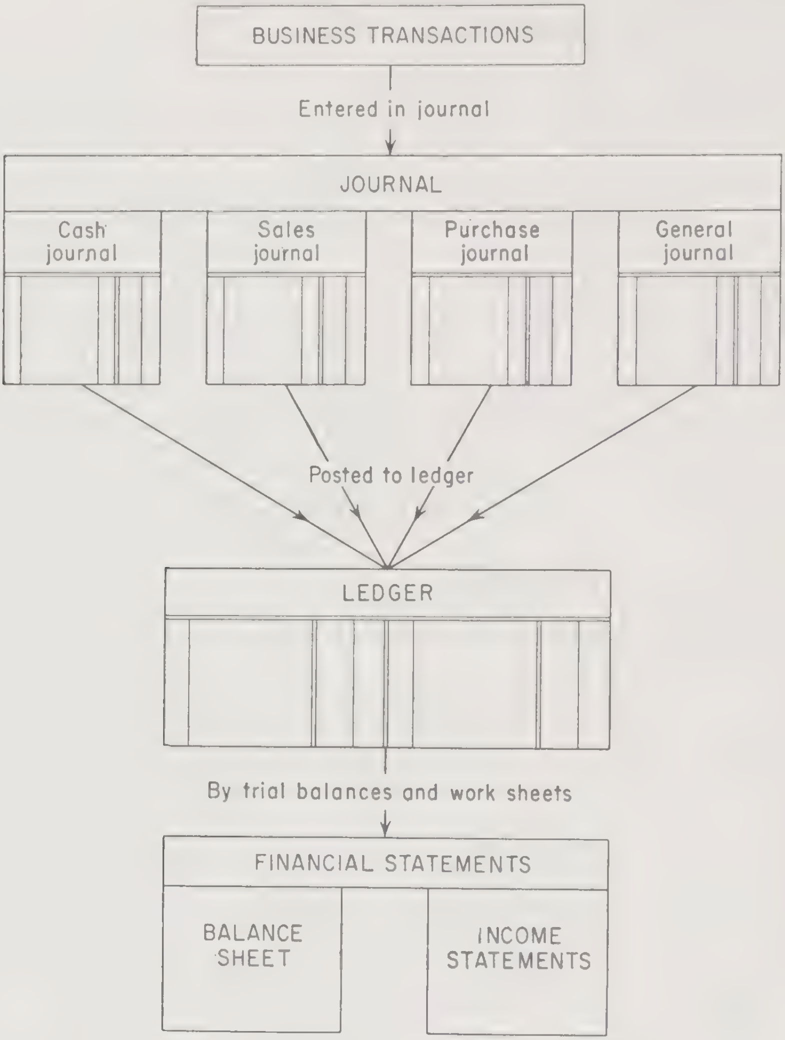

FIG. 8-1. Diagram of accounting procedure.

The next step is to assemble the journal entries under appropriate account headings in the *ledger*. The process of transferring the daily journal entries to the ledger is called *posting*.

Statements showing the financial condition of the business concern are prepared periodically from the ledger accounts. These statements are presented in the form of *balance sheets* and *income statements*. The balance sheet shows the financial condition of the business at a particular time, while the income statement is a record of the financial gain or loss of the organization over a given period of time.

THE BASIC RELATIONSHIPS IN ACCOUNTING

In the broadest sense, an *asset* may be defined as anything of value, such as cash, land, equipment, raw materials, finished products, or any type of property. At any given instant, a business concern has a certain monetary value because of its *assets*. At the same instant, many different persons may have a just claim, or *equity*, to ownership of the concern's assets. Certainly, any creditors would have a just claim to partial ownership, and the owners of the business should have some claim to ownership. Under these conditions, a fundamental relationship in accounting can be written as

$$\text{Assets} = \text{equities} \qquad (1)$$

Equities can be divided into two general classes as follows: (1) *Proprietorship*—the claims of the concern or person who owns the asset; and (2) *liabilities*—the claims of anyone other than the owner. The term *proprietorship* is often referred to as *net worth* or simply as *ownership* or *capital*. Thus, Eq. (1) can be written as *

$$\text{Assets} = \text{liabilities} + \text{proprietorship} \qquad (2)$$

The meaning of this basic equation can be illustrated by the following simple example. Five boys have gone together and purchased a second-hand automobile worth $1000. Because they did not have the necessary $1000 they borrowed $400 from one of the boys' fathers. Therefore, as far as the five boys are concerned, the value of their asset is $1000, their proprietorship is $600, and their liability is $400.

Equation (2) is the basis for balancing assets against equities at any given instant. A similar equation can be presented for balancing costs and profits over any given time period. The total income must be equal to the sum of all costs and profits, or

$$\text{Total income} = \text{costs} + \text{profits} \qquad (3)$$

Any engineering accounting study can ultimately be reduced to one of the forms represented by Eq. (2) or (3).

THE BALANCE SHEET

A balance sheet for an industrial concern is based on Eq. (1) or (2) and shows the financial condition at any given date. The amount of detail included varies depending on the purpose. Consolidated balance sheets based on the last day of the fiscal year are included in the annual report of a corporation. These reports are intended for distribution to stockholders, and the balance sheets present the pertinent information without listing each individual asset and equity in detail.

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* Equation (2) is sometimes expressed simply as "Assets = liabilities," where "liabilities" is synonymous with "equities."

Assets are commonly divided into the classifications of current, fixed, and miscellaneous. *Current assets*, in principle, represent capital which can readily be converted into cash. Examples would be accounts receivable, inventories, cash, and marketable securities. These are *liquid assets*. On the other hand, *fixed assets*, such as land, buildings, and equipment, cannot be converted into immediate cash. Deferred charges, other investments, notes and accounts due after 1 year, and similar items are ordinarily listed as miscellaneous assets under separate headings.

Modern balance sheets often use the general term *liabilities* in place of *equities*. *Current liabilities* are grouped together and include all liabilities which are due within 12 months of the balance-sheet date. They include accounts payable, debts, and tax accruals. The *net working capital* of a company can be obtained directly from the balance sheet as the difference between current assets and current liabilities. Other liabilities, such as long-term debts, deferred credits, and reserves are listed under separate headings. Proprietorship, stockholders' equity, or capital stock and surplus complete the record on the equity (or liability) side of the balance sheet.

Consolidated balance sheets are ordinarily presented with assets listed on the left and liabilities, including proprietorship, listed on the right. As indicated in Eq. (1), the total value of the assets must equal the total value of the equities. A typical balance sheet of this type is presented in Fig. 8-2.

The value of property items, such as land, buildings, and equipment, is usually reported as the value of the asset at the time of purchase. Depreciation reserves are also indicated, and the difference between the original property cost and the depreciation reserve represents the book value of the property. Thus, in depreciation accounting, separate records showing accumulation in the depreciation reserve must be maintained. In the customary account, *reserve for depreciation* is not actually a separate fund but is merely a bookkeeping method for recording the decline in property value.

The ratio of total current assets to total current liabilities is called the *current ratio*. The ratio of immediately available cash (i.e., cash plus U.S. Government and other marketable securities) to total current liabilities is known as the *cash ratio*. The current and cash ratios are valuable for determining the ability to meet financial obligations, and these ratios are examined carefully by banks or other loan concerns before credit is extended. From the data presented in Fig. 8-2, the current ratio for the company on December 31, 1954, was \$261,634,701/\$110,945,354 = 2.36, and the cash ratio was \$87,994,028/\$110,945,354 = 0.793.

PHILLIPS PETROLEUM COMPANY
CONSOLIDATED BALANCE SHEET AT DECEMBER 31, 1954

Assets	
Current assets:	
Cash	$ 87,994,028
Notes and accounts receivable (less reserve)	74,712,929
Inventories:	
Crude oil, petroleum products, and merchandise	77,878,176
Materials and supplies	21,049,568
Total current assets	$ 261,634,701
Fixed assets:	
Properties, plants, and equipment—at cost:	
Oil and gas	$ 767,659,105
Manufacturing	322,118,162
Transportation	121,264,835
Marketing	80,134,741
Other	47,225,024
	$1,338,401,867
Less—reserve for depreciation, depletion, and amortization	539,041,637
Total fixed assets (net)	$ 799,360,230
Notes and accounts receivable—due after 1 year (less reserve)	$ 7,795,392
Investments (at cost—less reserve)	$ 14,446,710
Prepaid and deferred charges	$ 9,507,982
TOTAL ASSETS	$1,092,745,015

Liabilities and stockholders' equity	
Current liabilities:	
Accounts payable	$ 55,555,471
Debts—due within 1 year	16,121,227
Accrued taxes	30,484,757
Other accruals	8,783,899
Total current liabilities	$ 110,945,354
Long-term debts	$ 265,317,007
Deferred credits:	
Federal income taxes	$ 12,625,355
Other	1,362,065
Total deferred credits	$ 13,987,420
Reserves:	
Insurance	$ 2,000,000
Contingencies	7,316,789
Total reserves	$ 9,316,789
Stockholders' equity:	
Common stock—14,653,120 shares issued and outstanding	$ 296,044,861
Excess of net assets of a subsidiary over cost	1,431,827
Earnings employed in the business	395,701,757
Total stockholders' equity	$ 693,178,445
TOTAL LIABILITY AND STOCKHOLDERS' EQUITY	$1,092,745,015

FIG. 8-2. A consolidated balance sheet.

THE INCOME STATEMENT

A balance sheet applies only at one specific time, and any additional transactions cause it to become obsolete. Most of the changes that occur in the balance sheet are due to revenue received from the sale of goods or services and costs incurred in the production and sale of the goods or services. Income-sheet accounts of all income and expense items, such as sales, purchases, depreciation, wages, salaries, taxes, and insurance, are maintained, and these accounts are summarized periodically in *income statements.*

A consolidated income statement is based on a given time period. It indicates surplus capital and shows the relationship among total income, costs, and profits over the time interval. The transactions presented in income-sheet accounts and income statements, therefore, are of particular interest to the engineer, since they represent the facts which he has attempted to predict through cost and profit analyses.

When the accountant refers to *gross income* or *gross revenue*, he means the total amount of capital received as a result of the sale of goods or

MONSANTO CHEMICAL COMPANY AND CONSOLIDATED SUBSIDIARIES
CONSOLIDATED INCOME STATEMENT FOR THE YEAR
ENDING DECEMBER 31, 1954

Income:	
Net sales	$341,822,557
Dividends from subsidiary and associated companies	798,483
Other	2,534,202
Total (or gross) income	$345,155,242
Deductions:	
Cost of goods sold	$243,057,056
Selling and administrative expenses	42,167,634
Research expenses	10,651,217
Provision for employees' bonus	649,319
Interest expense	3,323,372
Net income applicable to minority interests	143,440
Other	2,608,694
Total deductions	$302,600,732
Income before provision for income taxes	$ 42,554,510
Less provision for income taxes	18,854,000
Net income (net profit)	$ 23,700,510
Earned surplus at beginning of year	90,436,909
Total surplus	$114,137,419
Surplus deductions:	
Preferred dividends ($3.85 per share)	$ 721,875
Common dividends ($2.50 per share)	13,148,300
Total surplus deductions	$ 13,870,175
EARNED SURPLUS AT END OF YEAR	$100,267,244

FIG. 8-3. A consolidated income statement.

services. *Net income* or *net revenue* is the total profit remaining after deducting all costs, including taxes.

Figure 8-3 is a typical example of a consolidated income statement based on a time period of 1 year. As indicated by Eq. (3), the total income (\$345,155,242) equals total cost (\$302,600,732 + \$18,854,000) plus net income or profit (\$23,700,510).

The role of interest on borrowed capital is clearly indicated in Fig. 8-3. Since the accountant considers interest as an expense arising from the particular method of financing, the cost due to interest is listed as a separate expense.

MAINTAINING ACCOUNTING RECORDS

Balance sheets and income statements are summarizing records showing the important relationships among assets, liabilities, income, and costs at one particular time or over a period of time. Some method must be used for recording the day-to-day events. This is accomplished by the use of *journals* and *ledgers*.

A journal is a book, group of vouchers, or some other convenient substitute in which the original record of a transaction is listed, while a ledger is a group of accounts giving condensed and classified information from the journal.

Debits and Credits. When recording business transactions, a *debit* entry represents an addition to an account, while a *credit* entry represents a deduction from an account. In more precise terms, a debit entry is one which increases the assets or decreases the equities, and a credit entry is one which decreases the assets or increases the equities.

Since bookkeeping accounts must always show a balance between assets and equities, any single transaction must affect both assets and equities. Each debit entry, therefore, requires an equal and offsetting credit entry. For example, if a company purchased a piece of equipment by a cash payment, the assets of the company would be increased by the value of the equipment. This represents an addition to the account, and would, therefore, be listed as a debit. However, the company had to pay out cash to obtain the equipment. This payment must be recorded as a credit entry, since it represents a deduction from the account. At least one debit entry and one credit entry must be made for each business transaction in order to maintain the correct balance between assets and equities. This is known as *double-entry bookkeeping*.

The Journal. A typical example of a journal page is shown in Fig. 8-4. The date is indicated in the first two columns. An analysis of the account affected by the particular transaction is listed in the third column, with debits listed first and credits listed below and offset to the right. A brief description of the item is included if necessary. The amounts of the individual debit and credit entries are indicated in the last two columns, with debits always shown on the left. When the journal entry is posted in the ledger, the number of the ledger account or the page number is entered in the fourth column of the journal page. This column is usually designated by "F" for "Folio."

JOURNAL

Page 1

Date 19__		Analysis	F	Debit	Credit
April	3	Salaries	403	$ 758 00	$
		Cash	112		758 00
		Payment of salaries for week ending April 3			
	4	Rent	314	300 00	
		Cash	112		300 00
		Building rental for month of April			
	5	Cash	112	1041 00	
		Sales	201		1041 00
		Product *A* to X Company as per invoice No. 6839			
	8	Equipment	104	1800 00	
		Notes payable	521		1800 00
		Equipment for plant—6%, 90-day note to Y Company			
	9	Purchases	608	88 00	
		Z Company	842		88 00
		Tools on open account—Terms—30 days			

FIG. 8-4. A typical journal page.

The Ledger. Separate ledger accounts may be kept for various items, such as cash, equipment, accounts receivable, inventory, accounts payable, and manufacturing expense. A typical ledger sheet is shown in Fig. 8-5. The ledger sheets serve as a secondary record of business transactions and are used as the intermediates between journal records and balance sheets, income statements, and general cost records.

LEDGER

Cash 112

Date 19__		Analysis	F	Debit		Date 19__		Analysis	F	Credit	
April	1	Balance forward	J-1	$ 945	00	April	3	Salaries	J-1	$ 758	00
							4	Rent	J-1	300	00
	5	Sales	J-1	1041	00		10	Purchases	J-2	175	00
	10	Sales	J-2	86	00		12	Insurance	J-2	455	00
	11	R Company	J-2	700	00		13	Taxes	J-2	875	00
	11	Sales	J-2	550	00		17	Salaries	J-3	821	00
	12	Sales	J-2	94	00		21	Purchases	J-3	985	00
	18	S Company	J-3	1200	00		29	Office supplies	J-3	158	00
	22	Sales	J-3	175	00						
	28	Sales	J-3	548	00		30	Purchases	J-3	154	00
	29	Sales	J-3	630	00						
	30	Sales	J-3	74	00			Balance		1362	00
		Total		$6043	00			Total		$6043	00
		Balance forward		$1362	00						

FIG. 8-5. Typical ledger sheet that has been closed and balanced.

COST ACCOUNTING METHODS

In the simplest form, cost accounting is the determination and analysis of the cost of producing a product or rendering a service. This is exactly what the design engineer does when he estimates costs for a particular plant or process, and cost estimation is one type of cost accounting.

Accountants in industrial plants maintain records on actual expenditures for labor, materials, power, etc., and the maintenance and interpretation of these records is known as *actual* or *post-mortem* cost accounting. From these data, it is possible to make accurate predictions of the future cost of the particular plant or process. These predictions are very valuable for determining future capital requirements and income, and they represent an important type of cost accounting known as *standard* cost accounting. Deviations of standard costs from actual costs are designated as *variances*.

There are many different types of systems used for reporting costs, but all the systems employ some method for classifying the various expenses. One common type of classification corresponds to that presented in Chap. 2 (Costs in Chemical Processes) and Chap. 7 (Cost Estimation). The total cost is divided into the basic groups of factory manufacturing costs and general expenses. These are further subdivided, with administrative, distribution, selling, financing, and research and development costs included under general expenses. Factory manufacturing costs include direct production costs, fixed charges, and plant overhead.

Each of the subdivided groups can be further classified as indicated in Chaps. 2 and 7. For example, direct production costs can be broken down into costs for raw materials, labor, supervision, maintenance, overhead, supplies, power, utilities, and packaging.

Each concern has its own method for dividing up the costs on its accounts. In any case, all costs are entered in the appropriate journal account, posted in the ledger, and ultimately reported in a final cost sheet or cost statement.

Accumulation, Inventory, and Cost-of-sales Accounts. In general, basic cost-accounting methods require posting of all costs in so-called *accumulation accounts*. There may be a series of such accounts to handle the various costs for each product. At the end of a given time period, such as 1 month, the accumulated costs are transferred to *inventory* accounts, which give a summary of all expenditures during the particular time interval. The

MANUFACTURING COST WORKS INVENTORY

Refining of crude product *D* For month of January, 19__

Cost element		Units on hand		Units used per unit produced	Total units used or produced	Price per unit	Total cost	Cost per unit produced
Name	Unit	Start of month	End of month					
Crude product *D*...	Gallons	13,000	11,000	1.5000	150,000	$0.2787	$41,800	$0.4180
Operating wages...	Man-hours			0.0150	1,500	1.2500	1,975	0.0198
Operating supplies							890	0.0089
Maintenance wages	Man-hours			0.0250	2,500	2.0000	5,000	0.0500
Maintenance materials........							10,500	0.1050
Utilities...........							8,000	0.0800
Depreciation......	$ investment			5.0000	500,000	0.0100	5,000	0.0500
Overhead.........							3,800	0.0380
Total cost and production....	Gallons	5,000	4,000		100,000	$0.7697	$76,965	$0.7697

FIG. 8-6. Example of one type of inventory account.

amounts of all materials produced or consumed are also shown in the inventory accounts. The information in the inventory account is combined with data on the amount of product sales and transferred to the *cost-of-sales* account. The cost-of-sales accounts give the information necessary for determining the profit or loss for each product sold during the given time interval. One type of inventory account is shown in Fig. 8-6, and a sample cost-of-sales account is presented in Fig. 8-7.

COST-OF-SALES ACCOUNT

Product E For month of June, 19__

Item	This month	Last month	Year to date
Sales, lb	475,000	590,000	3,220,000
	$/unit	$/unit	$/unit
Selling price	$0.200	$0.200	$0.200
Cost of sales:			
Manufacturing cost	0.120	0.100	0.105
Freight and delivery	0.007	0.008	0.007
Selling expense	0.018	0.020	0.016
Administrative expense	0.025	0.020	0.022
Research expense	0.010	0.008	0.008
Total cost of sales	$0.180	$0.156	$0.158
Profits before taxes	$0.020	$0.044	$0.042

FIG. 8-7. Example of cost-of-sales account.

When several products or by-products are produced by the same plant, allocation of the cost to each product must be made on some predetermined basis. Although the allocation of raw-material and direct labor costs can be determined directly, the exact distribution of overhead costs may become quite complex, and the final method depends on the policies of the particular concern involved.

Materials Costs. The variation in costs due to price fluctuations can cause considerable difficulty in making the transfer from accumulation accounts to inventory and cost-of-sales accounts. For example, suppose an accumulation account showed the following:

ACCUMULATION ACCOUNT

ITEM: Chemical *A* for use in producing product *X*

Date 19__	Received	Cost	Balance on hand	Delivered for use in process
May 2.....	5,000 lb	$0.0360/lb	5,000 lb	
May 15....	10,000 lb	0.0390/lb	15,000 lb	
May 17....			9,000 lb	6,000 lb

In transferring the cost of chemical *A* to the inventory and cost-of-sales accounts, there is a question as to what price applies for chemical *A*. There are three basic methods for handling problems of this type.

1. *The current-average method.* The average price of all the inventory on hand at the time of delivery or use is employed. In the preceding example, the current-average price for chemical *A* would be $0.0380 per pound.

2. *The first-in first-out* (or *fifo*) *method.* This method assumes the oldest material is always used first. The price for the 6000 lb of chemical *A* would be $0.0360 per pound for the first 5000 lb and $0.0390 for the remaining 1000 lb.

3. *The last-in first-out* (or *lifo*) *method.* With this method, the most recent prices are always used. The price for the 6000 lb of chemical *A* would be transferred as $0.0390 per pound.

Any of these methods can be used. The current-average method presents the best picture of the true cost during the given time interval, but it may be misleading if used for predicting future costs.

The information presented in this chapter shows the general principles and fundamentals of accounting which are of direct interest to the engineer. However, the many aspects of accounting make it impossible to present a complete coverage of all details and systems in one chapter or even in one book.* The exact methods used in different businesses may vary widely depending on the purpose and the policies of the organization, but the basic principles are the same in all cases.

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PROBLEMS

1. Prepare a balance sheet applicable at the date when the X Corporation had the following assets and equities:

Cash	$20,000	Common stock sold	$50,000
Accounts payable:			
B Company	2,000	Machinery and equipment (at present value)	18,000
C Corporation	8,000		
Accounts receivable	6,000	Furniture and fixtures (at present value)	5,000
Inventories	15,000	Government bonds	3,000
Mortgage payable	5,000	Surplus	2,000

2. During the month of October, the following information was obtained in an antifreeze retailing concern:

Salaries	$ 3,000
Delivery expenses	700
Rent	400
Sales	15,100
Antifreeze available for sale during October (at cost)	20,200
Antifreeze inventory on Oct. 31 (at cost)	11,600
Other expenses	1,200
Earned surplus before income taxes as of Sept. 30	800

Prepare an income statement for the month of October giving as much detail as possible.

3. The following information applies to E Company on a given date:

Long-term debts	$ 1,600
Debts due within 1 year	1,000
Accounts payable	2,300
Machinery and equipment (at cost)	10,000
Cash in bank	3,100
Prepaid rent	300
Government bonds	3,000
Social security taxes payable	240
Reserve for depreciation	600
Reserve for expansion	1,200
Inventory	1,600
Accounts receivable	1,700

Determine the current ratio, cash ratio, and working capital for Company E at the given date.

4. On Aug. 1, a concern had 10,000 lb of raw material on hand which was purchased at a cost of $0.030 per pound. In order to build up the reserve, 8000 lb of additional raw material was purchased on Aug. 15 at a cost of $0.028 per pound, and 2 days later

6000 lb was purchased from another supplier at $0.031 per pound. If none of the raw material was used until after the last purchase, determine the total cost of 12,000 lb of the raw material on an inventory or cost-of-sales account for the month of August by (*a*) the current-average method, (*b*) the "fifo" method, and (*c*) the "lifo" method.

5. Prepare a complete list, with sample form sheets, of all cost-accounting records which should be maintained in a large plant producing ammonia, nitric acid, and ammonium nitrate. Explain how these records are used in recording, summarizing, and interpreting costs and profits.

CHAPTER 9

OPTIMUM DESIGN

An optimum design is based on the best or most favorable conditions. In almost every case, these optimum conditions can ultimately be reduced to a consideration of costs or profits. Thus, an optimum economic design could be based on conditions giving the least cost per unit of time or the maximum profit per unit of production. When one design variable is changed, it is often found that some costs increase and others decrease. Under these conditions, the total cost may go through a minimum at one value of the particular design variable, and this value would be considered as an optimum.

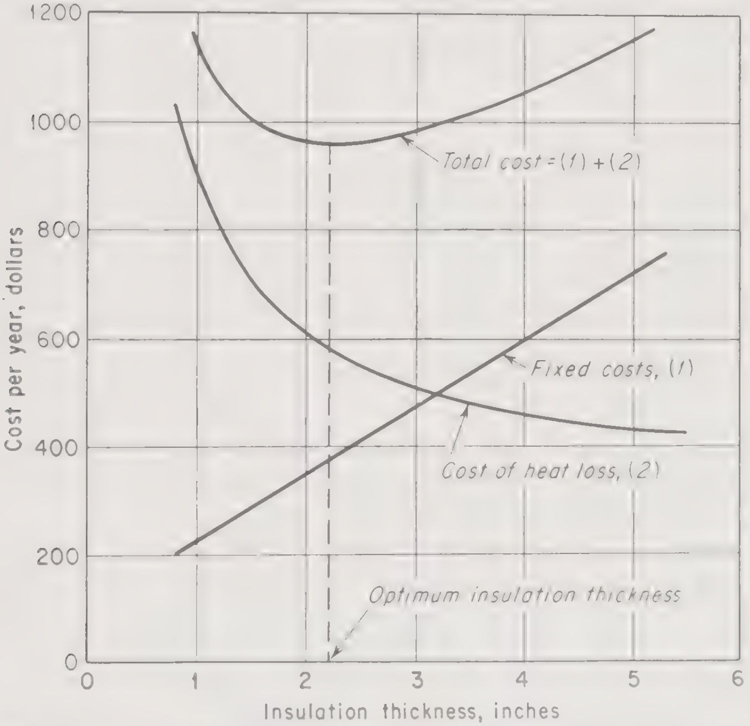

FIG. 9-1. Illustration of the basic principle of an optimum design.

An example illustrating the principles of an optimum economic design is presented in Fig. 9-1. In this simple case, the problem is to determine the optimum thickness of insulation for a given steam-pipe installation. As the insulation thickness is increased, the annual fixed costs increase, the cost of heat loss decreases, and all other costs remain constant. Therefore, as shown in Fig. 9-1, the sum of the costs must go through a minimum at the optimum insulation thickness.

Although cost considerations and economic balances are the basis of most optimum designs, there are times when factors other than cost can determine the most favorable conditions. For example, in the operation of a catalytic reactor, an optimum operation temperature may exist for each reactor size because of equilibrium and reaction-rate limitations. This particular temperature could be based on the maximum percentage conversion or on the maximum amount of final product per unit of time. Ultimately, however, cost variables need to be considered, and the development of an optimum operation design is usually merely one step in the determination of an optimum economic design.

INCREMENTAL COSTS

The subject of incremental costs is covered in detail in Chap. 6 (Alternative Investments and Replacements). Consideration of incremental costs shows that a final recommended design does not need to correspond to the optimum economic design, because the incremental return on the added investment may become unacceptable before the optimum point is reached.* However, the optimum values can be used as a basis for starting the incremental-cost analyses.

This chapter deals with methods for determining optimum conditions, and it is assumed that the reader understands the role of incremental costs in establishing a final recommended design.

GENERAL PROCEDURE FOR DETERMINING OPTIMUM CONDITIONS

The first step in the development of an optimum design is to determine what factor is to be optimized. Typical factors would be total cost per unit of production or per unit of time, profit, amount of final product per unit of time, and per cent conversion. Once the basis is determined, it is necessary to develop relationships showing how the different variables involved affect the chosen factor. Finally, these relationships are combined graphically or analytically to give the desired optimum conditions.

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* See Fig. 6-2 and the related discussion in Chap. 6. The material presented in Chap. 9 considers optimum designs based on maximum or minimum values of a specified variable. The same type of approach could be used if the term *optimum* (referring to an investment) were defined on the basis of a stipulated incremental return.

Procedure with One Variable

There are many cases in which the factor being optimized is a function of a single variable. The procedure then becomes very simple. Consider the example presented in Fig. 9-1, where it is necessary to obtain the insulation thickness which gives the least total cost. The primary variable involved is the thickness of the insulation, and relationships can be developed showing how this variable affects all costs.

Cost data for the purchase and installation of the insulation are available, and the length of service life can be estimated. Therefore, a relationship giving the effect of insulation thickness on fixed charges can be developed. Similarly, a relationship showing the cost of heat lost as a function of insulation thickness can be obtained from data on the value of steam, properties of the insulation, and heat-transfer considerations. All other costs, such as maintenance and plant expenses, can be assumed to be independent of the insulation thickness.

The two cost relationships obtained might be expressed in a simplified form similar to the following:

$$\text{Fixed charges} = \phi(x) = ax + b \tag{1}$$

$$\text{Cost of heat loss} = \phi^{i}(x) = \frac{c}{x} + d \tag{2}$$

$$\text{Total variable cost} = C_T = \phi(x) + \phi^{i}(x) = \phi^{ii}(x)$$

$$= ax + b + \frac{c}{x} + d \tag{3}$$

where a, b, c, and d are constants and x is the common variable (insulation thickness).

The *graphical* method for determining the optimum insulation thickness is shown in Fig. 9-1. The optimum thickness of insulation is found at the minimum point on the curve obtained by plotting total variable cost versus insulation thickness.

The slope of the total-variable-cost curve is zero at the point of optimum insulation thickness. Therefore, if Eq. (3) applies, the optimum value can be found *analytically* by merely setting the derivative of C_T with respect to x equal to zero and solving for x.

$$\frac{dC_T}{dx} = a - \frac{c}{x^2} = 0 \tag{4}$$

$$x = \left(\frac{c}{a}\right)^{1/2} \tag{5}$$

If the factor being optimized (C_T) does not attain a usable maximum or minimum value, the solution for the dependent variable will indicate this condition by giving an impossible result, such as infinity, zero, or the square root of a negative number.

The value of x shown in Eq. (5) occurs at an optimum point or a point of inflection. The second derivative of Eq. (3), evaluated at the given point, indicates if the value occurs at a minimum (second derivative greater than zero), maximum (second derivative less than zero), or point of inflection (second derivative equal to zero). An alternative method for determining the type of point involved is to calculate values of the factor being optimized at points slightly greater and slightly smaller than the optimum value of the dependent variable.

The second derivative of Eq. (3) is

$$\frac{d^2C_T}{dx^2} = +\frac{2c}{x^3} \tag{6}$$

If x represents a variable such as insulation thickness, its value must be positive; therefore, if c is positive, the second derivative at the optimum point must be greater than zero, and $(c/a)^{1/2}$ represents the value of x at the point where the total variable cost is a minimum.

Procedure with Two or More Variables

When two or more independent variables affect the factor being optimized, the procedure for determining the optimum conditions may become rather tedious; however, the general approach is the same as when only one variable is involved.

Consider the case in which the total cost for a given operation is a function of the two independent variables x and y, or

$$C_T = \phi^{iii}(xy) \tag{7}$$

By analyzing all the costs involved and reducing the resulting relationships to a simple form, the following function might be found for Eq. (7):

$$C_T = ax + \frac{b}{xy} + cy + d \tag{8}$$

where a, b, c, and d are positive constants.

Graphical Procedure. The relationship among C_T, x, and y could be shown as a curved surface in a three-dimensional plot, with a minimum value of C_T occurring at the optimum values of x and y. However, the use of a three-dimensional plot is not practical for most engineering determinations.

The optimum values of x and y in Eq. (8) can be found graphically on a two-dimensional plot by using the method indicated in Fig. 9-2. In this figure, the factor being optimized is plotted against one of the independent variables (x), with the second variable (y) held at a constant value. A series of such plots is made with each dashed curve representing a different constant value of the second variable. As shown in Fig. 9-2, each of the curves (A, B, C, D, and E) gives one value of the first variable x at the point where the total cost is a minimum. The curve NM represents the locus of all these minimum points, and the optimum value of x and y occurs at the minimum point on curve NM.

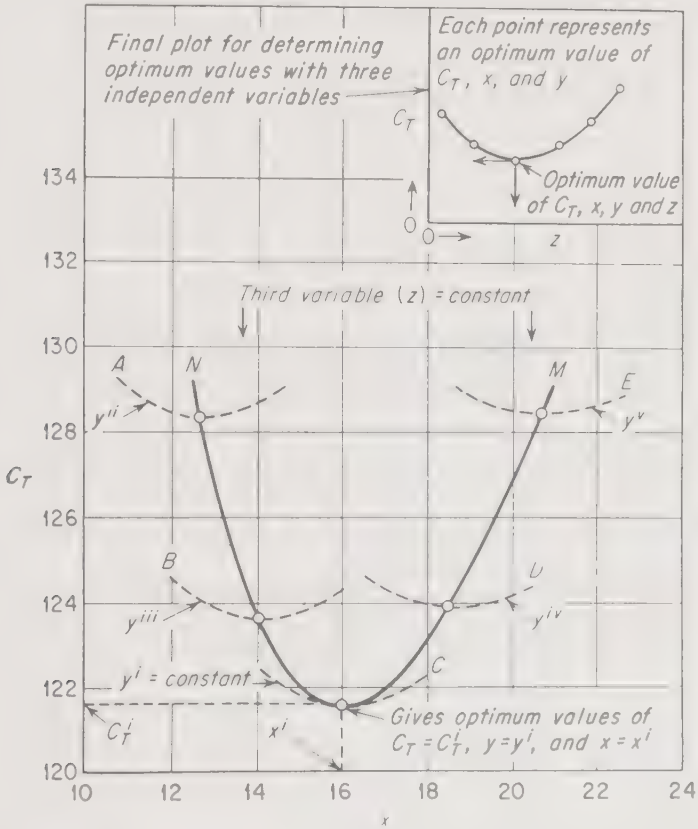

Fig. 9-2. Graphical determination of optimum conditions with two or more independent variables.

Similar graphical procedures can be used when there are more than two independent variables. For example, if a third variable z were included in Eq. (8), the first step would be to make a plot similar to Fig. 9-2 at one constant value of z. Similar plots would then be made at other constant values of z. Each plot would give an optimum value of x, y, and C_T for a particular z. Finally, as shown in the insert in Fig. 9-2, the over-all optimum value of x, y, z, and C_T could be obtained by plotting z versus the individual optimum values of C_T.

Analytical Procedure. In Fig. 9-2, the optimum value of x is found at the point where $\left(\frac{\partial C_T}{\partial x}\right)_{y=y^i}$ is equal to zero. Similarly, the same results would be obtained if y were used as the abscissa instead of x. If this were done, the optimum value of y (i.e., y') would be found at the point where $\left(\frac{\partial C_T}{\partial y}\right)_{x=x^i}$ is equal to zero. This immediately indicates an analytical procedure for determining optimum values.

Using Eq. (8) as a basis,

$$\frac{\partial C_T}{\partial x} = a - \frac{b}{x^2y} \tag{9}$$

$$\frac{\partial C_T}{\partial y} = c - \frac{b}{xy^2} \tag{10}$$

At the optimum conditions, both of these partial derivatives must be equal to zero; thus, Eqs. (9) and (10) can be set equal to zero and the optimum values of $x = (cb/a^2)^{1/3}$ and $y = (ab/c^2)^{1/3}$ can be obtained by solving the two simultaneous equations. If more than two independent variables were involved, the same procedure would be followed, with the number of simultaneous equations being equal to the number of independent variables.

Example 1. Determination of Optimum Values with Two Independent Variables. The following equation shows the effect of the variables x and y on the total cost for a particular operation:

$$C_T = 2.33x + \frac{11{,}900}{xy} + 1.86y + 10$$

Determine the values of x and y which will give the least total cost

Solution

Analytical method:

$$\frac{\partial C_T}{\partial x} = 2.33 - \frac{11{,}900}{x^2y}$$

$$\frac{\partial C_T}{\partial y} = 1.86 - \frac{11{,}900}{xy^2}$$

At the optimum point,

$$2.33 - \frac{11{,}900}{x^2y} = 0$$

$$1.86 - \frac{11{,}900}{xy^2} = 0$$

Solving simultaneously for the optimum values of x and y,

$$x = 16$$

$$y = 20$$

$$C_T = 121.6$$

A check should be made to make certain the preceding values represent conditions of minimum cost.

$$\frac{\partial^2 C_T}{\partial x^2} = \frac{(2)(11{,}900)}{x^3 y} = \frac{(2)(11{,}900)}{(16)^3(20)} = + \text{ at optimum point}$$

$$\frac{\partial^2 C_T}{\partial y^2} = \frac{(2)(11{,}900)}{x y^3} = \frac{(2)(11{,}900)}{(16)(20)^3} = + \text{ at optimum point}$$

Since the second derivatives are positive, the optimum conditions must occur at a point of minimum cost.

Graphical method:

The following constant values of y are chosen arbitrarily:

$$y^{ii} = 32 \qquad y^{iii} = 26 \qquad y^{i} = 20 \qquad y^{iv} = 15 \qquad y^{v} = 12$$

At each constant value of y, a plot is made of C_T versus x. These plots are presented in Fig. 9-2 as curves A, B, C, D, and E. A summary of the results is presented in the following table:

y	Optimum x	Optimum C_T
$y^{ii} = 32$	12.7	128.3
$y^{iii} = 26$	14.1	123.6
$y^{i} = 20$	16.0	121.6
$y^{iv} = 15$	18.5	123.9
$y^{v} = 12$	20.7	128.5

One curve (NM in Fig. 9-2) through the various optimum points shows that the over-all optimum occurs at

$$x = 16$$

$$y = 20$$

$$C_T = 121.6$$

Note: In this case, a value of y was chosen which corresponded to the optimum value. Usually, it is necessary to interpolate or make further calculations in order to determine the final optimum conditions.

COMPARISON OF GRAPHICAL AND ANALYTICAL METHODS

In the determination of optimum conditions, the same final results are obtained with either graphical or analytical methods. Sometimes it is impossible to set up one analytical function for differentiation, and the graphical method must be used. If the development and simplification of the total analytical function requires complicated mathematics, it may be simpler to resort to the direct graphical solution; however, each individual problem should be analyzed on the basis of the existing circumstances. For example, if numerous repeated trials are necessary, the extra time required to develop an analytical solution may be well spent.

The graphical method has one distinct advantage over the analytical method. The shape of the curve indicates the importance of operating at or very close to the optimum conditions. If the maximum or minimum occurs at a point where the curve is flat with only a gradual change in slope, there will be a considerable spread in the choice of final conditions, and incremental cost analyses may be necessary. On the other hand, if the maximum or minimum is sharp, it may be essential to operate at the exact optimum conditions.

OPTIMUM PRODUCTION RATES IN PLANT OPERATION

The same principles used for developing an optimum design can be applied when determining the most favorable conditions in the operation of a manufacturing plant. One of the most important variables in any plant operation is the amount of product produced per unit of time. The production rate depends on many factors, such as the number of hours in operation per day, per week, or per month; the load placed on the equipment; and the sales market available. From an analysis of the costs involved under different situations and consideration of other factors affecting the particular plant, it is possible to determine an *optimum rate of production* or a so-called *economic lot size.*

When a design engineer submits a complete plant design, he ordinarily has based his work on a given production capacity for the plant. After the plant is put into operation, however, some of the original design factors will have changed, and the optimum rate of production may vary considerably from the "designed capacity." For example, suppose a plant had been designed originally for the batchwise production of an organic chemical on the basis of one batch every 8 hr. After the plant has been put into operation, cost data on the actual process are obtained, and tests with various operating procedures are conducted. It is found that more total production per month can be obtained if the time per batch is reduced. However, when the shorter batch time is used, more labor is required, the per cent conversion of raw materials is reduced, and steam and power costs increase. Here is an obvious case in which an economic balance can be used to find the optimum production rate. Although the design engineer may have based his original recommendations on a similar type of economic balance, price and market conditions do not remain constant, and the operations engineer now has actual results on which he can base his economic balance. The following analysis indicates the general method for determining economic production rates or lot sizes.

The total product cost per unit of time may be divided into the two classifications of *operating costs* and *organization costs*. Operating costs depend on the rate of production and include expenses for direct labor, raw materials, power, heat, supplies, and similar items which are a function of the amount of material produced. Organization costs are due to expenses for directive personnel, physical equipment, and other services or facilities which must be maintained irrespective of the amount of material produced. Organization costs are independent of the rate of production.

It is convenient to consider operating costs on the basis of one unit of production. When this is done, the operating costs can be divided into two types of expenses as follows: (1) Minimum expenses for raw materials, labor, power, etc., that remain constant and must be paid for each unit of production as long as any amount of material is produced; and (2) extra expenses due to increasing the rate of production. These extra expenses are known as *superproduction costs*. They become particularly important at high rates of production. Examples of superproduction costs are extra expenses caused by overload on power facilities, additional labor requirements, or decreased efficiency of conversion. Superproduction costs can often be represented as follows:

$$\text{Superproduction costs per unit of production} = mP^n \tag{11}$$

where P = rate of production as total units of production per unit of time

m = a constant

n = a constant

Designating h as the operating costs which remain constant per unit of production and O_c as the organization costs per unit of time, the total product cost c_T per unit of production is

$$c_T = h + mP^n + \frac{O_c}{P} \tag{12}$$

The following equations for various types of costs or profits are based on Eq. (12):

$$C_T = c_TP = \left(h + mP^n + \frac{O_c}{P}\right)P \tag{13}$$

$$r = s - c_T = s - h - mP^n - \frac{O_c}{P} \tag{14}$$

$$R = rP = \left(s - h - mP^n - \frac{O_c}{P}\right) P \tag{15}$$

where C_T = total product cost per unit of time
r = profit per unit of production
R = profit per unit of time
s = selling price per unit of production

Optimum Production Rate for Minimum Cost per Unit of Production

It is often necessary to know the rate of production which will give the least cost on the basis of one unit of material produced. This information shows the selling price at which the company would be forced to cease operation or else operate at a loss. At this particular optimum rate, a plot of the total product cost per unit of production versus the production rate shows a minimum product cost; therefore, the optimum production rate must occur where $dc_T/dP = O$. An analytical solution for this case may be obtained from Eq. (12), and the optimum rate P_o giving the minimum cost per unit of production is found as follows:

$$\frac{dc_T}{dP} = O = nmP_o^{\,n-1} - \frac{O_c}{P_o^{\,2}} \tag{16}$$

$$P_o = \left(\frac{O_c}{nm}\right)^{1/(n+1)} \tag{17}$$

The optimum rate shown in Eq. (17) would, of course, give the maximum profit per unit of production if the selling price remains constant.

Optimum Production Rate for Maximum Total Profit per Unit of Time

In most business concerns, the amount of money earned over a given time period is much more important than the amount of money earned for each unit of product sold. Therefore, it is necessary to recognize that the production rate for maximum profit per unit of time may differ considerably from the production rate for minimum cost per unit of production.

Equation (15) presents the basic relationship between costs and profits. A plot of profit per unit of time versus production rate goes through a maximum. Equation (15), therefore, can be used to find an analytical value of the optimum production rate. When the selling price remains constant, the optimum rate giving the maximum profit per unit of time is

$$P_o = \left[\frac{s - h}{(n + 1)m}\right]^{1/n} \tag{18}$$

Example 2. Determination of Profits at Optimum Production Rates. A plant produces refrigerators at the rate of P units per day. The variable costs per refrigerator have been found to be $\$47.73 + 0.1P^{1.2}$. The total daily fixed charges are \$1750, and all other expenses are constant at \$7325 per day. If the selling price per refrigerator is \$173, determine the daily profit:

(*a*) At a production schedule giving the minimum cost per refrigerator.

(*b*) At a production schedule giving the maximum daily profit.

Solution

(*a*) Total cost per refrigerator $= c_T = 47.73 + 0.1P^{1.2} + (1750 + 7325)/P$.

At production schedule for minimum cost per refrigerator,

$$\frac{dc_T}{dP} = 0 = 0.12P_o^{0.2} - \frac{9075}{P_o^2}$$

$$P_o = 165 \text{ units per day for minimum cost per unit}$$

Daily profit at production schedule for minimum cost per refrigerator

$$= \left[173 - 47.73 - 0.1(165)^{1.2} - \frac{9075}{165}\right] 165$$
$$= \$4040$$

(*b*) Daily profit is

$$R = \left(173 - 47.73 - 0.1P^{1.2} - \frac{1750 + 7325}{P}\right) P$$

At production schedule for maximum profit per day,

$$\frac{dR}{dP} = 0 = 125.27 - 0.22P_o^{1.2}$$

$$P_o = 198 \text{ units per day for maximum daily profit}$$

Daily profit at production schedule for maximum daily profit

$$= \left[173 - 47.73 - 0.1(198)^{1.2} - \frac{9075}{198}\right] 198$$
$$= \$4400$$

OPTIMUM CONDITIONS IN CYCLIC OPERATIONS

Many processes are carried out by the use of cyclic operations which involve periodic shutdowns for discharging, cleanout, or reactivation. This type of operation occurs when the product is produced by a batch process or when the rate of production decreases with time, as in the operation of a plate-and-frame filtration unit. In a true batch operation, no product is obtained until the unit is shut down for discharging. In semicontinuous cyclic operations, product is delivered continuously while the unit is in operation, but the rate of delivery decreases with time. Thus, in batch or semicontinuous cyclic operations, the variable of total time required per cycle must be considered when determining optimum conditions.

Analyses of cyclic operations can be carried out conveniently by using the time for one cycle as a basis. When this is done, relationships similar to the following can be developed to express over-all factors, such as total annual cost or annual rate of production:

$$\text{Total annual cost} = \text{operating and shutdown costs/cycle} \times \text{cycles/year} + \text{annual fixed costs} \tag{19}$$

$$\text{Annual production} = (\text{production/cycle})(\text{cycles/year}) \tag{20}$$

$$\text{Cycles/year} = \frac{\text{operating} + \text{shutdown time used/year}}{\text{operating} + \text{shutdown time/cycle}} \tag{21}$$

The following example illustrates the general method for determining optimum conditions in a batch operation.

Example 3. Determination of Conditions for Minimum Total Cost in a Batch Operation. An organic chemical is being produced by a batch operation in which no product is obtained until the batch is finished. Each cycle consists of the operating time necessary to complete the reaction plus a total time of 1.4 hr for discharging and charging. The operating time per cycle is equal to $1.5P_b^{0.25}$ hr, where P_b is the pounds of product produced per batch. The operating costs during the operating period are \$20 per hour, and the costs during the discharge-charge period are \$15 per hour. The annual fixed costs for the equipment vary with the size of the batch as follows:

$$C_F = 340P_b^{0.8} \text{ dollars per batch}$$

Inventory and storage charges may be neglected. If necessary, the plant can be operated 24 hr per day for 300 days per year. The annual production is 1 million lb of product. At this capacity, raw-material and miscellaneous costs, other than those already mentioned, amount to \$260,000 per year. Determine the cycle time for conditions of minimum total cost per year.

Solution

$$\text{Cycles/year} = \frac{\text{annual production}}{\text{production/cycle}} = \frac{1{,}000{,}000}{P_b}$$

$\text{Cycle time} = \text{operating} + \text{shutdown time} = 1.5P_b^{0.25} + 1.4 \text{ hr}$

$\text{Operating} + \text{shutdown costs/cycle} = (20)(1.5P_b^{0.25}) + (15)(1.4) \text{ dollars}$

$\text{Annual fixed costs} = 340P_b^{0.8} + 260{,}000 \text{ dollars}$

$\text{Total annual costs} = (30P_b^{0.25} + 21)(1{,}000{,}000/P_b) + 340P_b^{0.8} + 260{,}000 \text{ dollars}$

The total annual cost is a minimum where $d(\text{total annual cost})/dP_b = 0$. Performing the differentiation, setting the result equal to zero, and solving for P_b give

$$P_{b,\text{optimum cost}} = 1630 \text{ lb per batch}$$

This same result could have been obtained by plotting total annual cost versus P_b and determining the value of P_b at the point of minimum annual cost.

For conditions of minimum annual cost and 1 million lb/year production,

$$\text{Cycle time} = (1.5)(1630)^{0.25} + 1.4 = 11 \text{ hr}$$

$$\text{Total time used per year} = (11)\left(\frac{1{,}000{,}000}{1630}\right) = 6750 \text{ hr}$$

$$\text{Total time available per year} = (300)(24) = 7200 \text{ hr}$$

Thus, for conditions of minimum annual cost and a production of 1 million lb per year, not all the available operating and shutdown time would be used.

Semicontinuous Cyclic Operations

Semicontinuous cyclic operations are often encountered in the chemical industry, and the design engineer should understand the methods for determining optimum cycle times in this type of operation. Although product is delivered continuously, the rate of delivery decreases with time owing to scaling, collection of side product, reduction in conversion efficiency, or similar causes. It becomes necessary, therefore, to shut down the operation periodically in order to restore the original conditions for high production rates. The optimum cycle time can be determined for conditions such as maximum amount of production per unit of time or minimum cost per unit of production.

Scale Formation in Evaporation. During the time an evaporator is in operation, solids often deposit on the heat-transfer surfaces, forming a scale. The continuous formation of the scale causes a gradual increase in the resistance to the flow of heat and, consequently, a reduction in the rate of heat transfer and rate of evaporation if the same temperature-difference driving forces are maintained. Under these conditions, the evaporation unit must be shut down and cleaned after an optimum operation time, and the cycle is then repeated.

Scale formation occurs to some extent in all types of evaporators, but it is of particular importance when the feed mixture contains a dissolved material that has an inverted solubility. The expression *inverted solubility* means the solubility decreases as the temperature of the solution is increased. For a material of this type, the solubility is least near the heat-transfer surface where the temperature is the greatest. Thus, any solid crystallizing out of the solution does so near the heat-transfer surface and is quite likely to form a scale on this surface. The most common scale-forming substances are calcium sulfate, calcium hydroxide, sodium carbonate, sodium sulfate, and calcium salts of certain organic acids.

When true scale formation occurs, the over-all heat-transfer coefficient may be related to the time the evaporator has been in operation by the straight-line equation *

$$\frac{1}{U^2} = a\theta_b + d \tag{22}$$

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* W. McCabe and C. Robinson, *Ind. Eng. Chem.*, **16**:478 (1924).

where a and d are constants for any given operation and U is the over-all heat-transfer coefficient at any operating time θ_b since the beginning of the operation.

If it is not convenient to determine the heat-transfer coefficients and the related constants as shown in Eq. (22), any quantity that is proportional to the heat-transfer coefficient may be used. Thus, if all conditions except scale formation are constant, feed rate, production rate, and evaporation rate can each be represented in a form similar to Eq. (22). Any of these equations can be used as a basis for finding the optimum conditions. The general method is illustrated by the following treatment, which employs Eq. (22) as a basis.

If Q represents the total amount of heat transferred in the operating time θ_b, and A and Δt represent, respectively, the heat-transfer area and temperature-difference driving force, the rate of heat transfer at any instant is

$$\frac{dQ}{d\theta_b} = UA\ \Delta t = \frac{A\ \Delta t}{(a\theta_b + d)^{1/2}} \tag{23}$$

The instantaneous rate of heat transfer varies during the time of operation, but the heat-transfer area and the temperature-difference driving force remain essentially constant. Therefore, the total amount of heat transferred during an operating time of θ_b can be determined by integrating Eq. (23) as follows:

$$\int_0^Q dQ = A\ \Delta t \int_0^{\theta_b} \left(\frac{1}{a\theta_b + d}\right)^{1/2} d\theta_b \tag{24}$$

$$Q = \frac{2A\ \Delta t}{a}\left[(a\theta_b + d)^{1/2} - d^{1/2}\right] \tag{25}$$

Cycle Time for Maximum Amount of Heat Transfer. Equation (25) can be used as a basis for finding the cycle time which will permit the maximum amount of heat transfer during a given period. Each cycle consists of an operating (or boiling) time of θ_b hr. If the time per cycle for emptying, cleaning, and recharging is θ_c, the total time in hours per cycle is $\theta_t = \theta_b + \theta_c$. Therefore, designating the total time *used* for actual operation, emptying, cleaning, and refilling as H, the number of cycles during H hr $= H/(\theta_b + \theta_c)$.

The total amount of heat transferred during H hr $= Q_H =$ (Q per cycle) × (cycles per H hr). Therefore,

$$Q_H = \frac{2A\ \Delta t}{a}\left[(a\theta_b + d)^{1/2} - d^{1/2}\right]\frac{H}{\theta_b + \theta_c} \tag{26}$$

Under ordinary conditions, the only variable in Eq. (26) is the operating time θ_b. A plot of the total amount of heat transferred versus θ_b shows a maximum at the optimum value of θ_b. Figure 9-3 presents a plot of this type. The optimum cycle time can also be obtained by setting the derivative of Eq. (26) with respect to θ_b equal to zero and solving for θ_b. The result is

$$\theta_{b,\text{per cycle for maximum amount of heat transfer}} = \theta_c + \frac{2}{a}\sqrt{a\,d\,\theta_c} \tag{27}$$

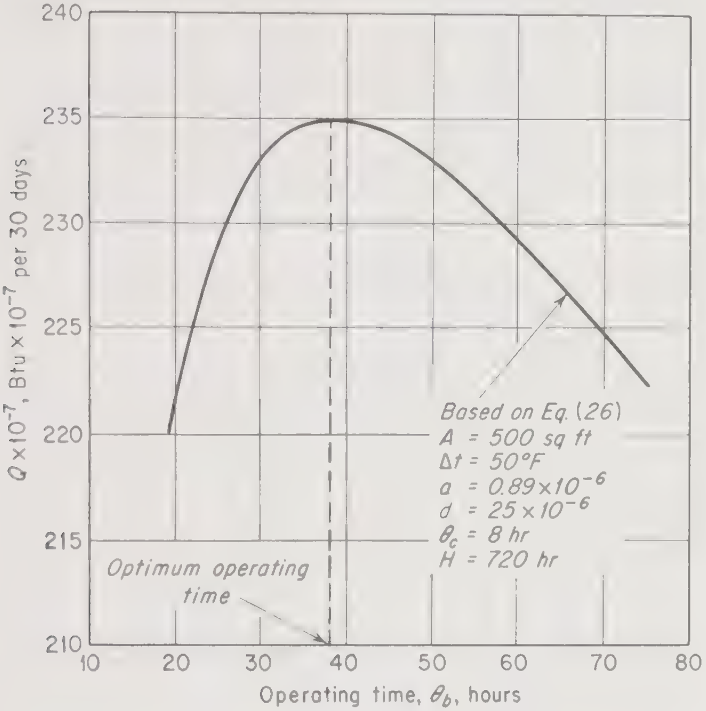

FIG. 9-3. Determination of optimum operating time for maximum amount of heat transfer in evaporator with scale formation.

The optimum boiling time given by Eq. (27) shows the operating schedule necessary to permit the maximum amount of heat transfer. All the time available for operation, emptying, cleaning, and refilling should be used. For constant operating conditions, this same schedule would also give the maximum amount of feed consumed, product obtained, and liquid evaporated.

A third method for determining the optimum cycle time is known as the *tangential method for finding optimum conditions*, and it is applicable to many types of cyclic operations. This method is illustrated for conditions of constant cleaning time (θ_c) in Fig. 9-4, where a plot of amount of heat transferred versus boiling time is presented. Curve OB is based on Eq.

(25). The *average* amount of heat transferred per unit of time during one complete cycle is $Q/(\theta_b + \theta_c)$. When the total amount of heat transferred during a number of repeated cycles is a maximum, the average amount of heat transferred per unit of time must also be a maximum. The optimum cycle time, therefore, occurs when $Q/(\theta_b + \theta_c)$ is a maximum.

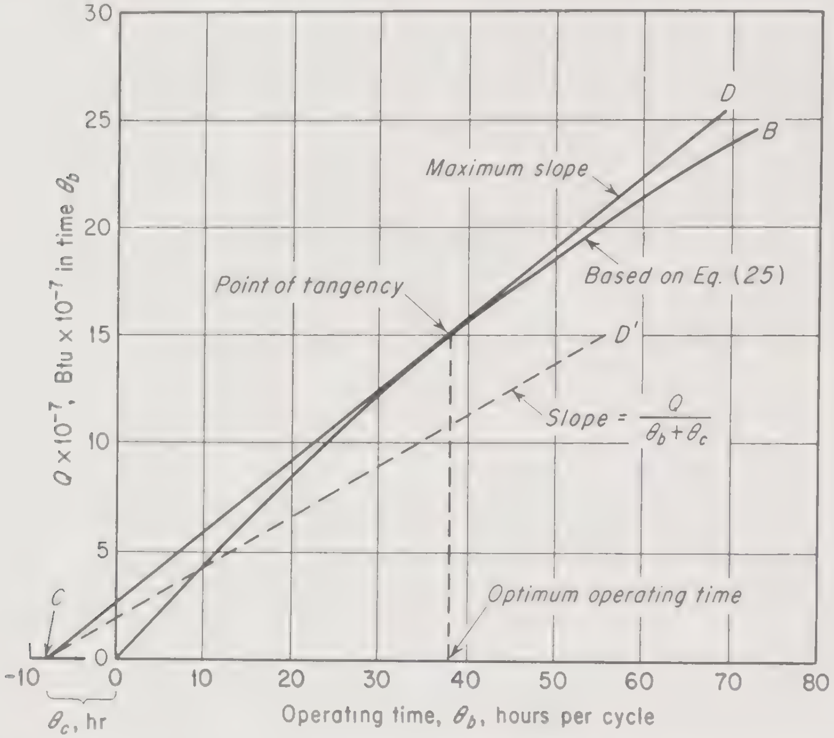

FIG. 9-4. Tangential method for finding optimum operating time for maximum amount of heat transfer in evaporator with scale formation.

The straight line CD' in Fig. 9-4 starts at a distance equivalent to θ_c on the left of the plot origin. The slope of this straight line is $Q/(\theta_b + \theta_c)$, with the values of Q and θ_b determined by the point of intersection between line CD' and curve OB. The maximum value of $Q/(\theta_b + \theta_c)$ occurs when line CD is tangent to the curve OB, and the point of tangency indicates the optimum value of the boiling time per cycle for conditions of maximum amount of heat transfer.

Cycle Time for Minimum Cost per Unit of Heat Transfer. There are many different circumstances which may affect the minimum cost per unit of heat transferred in an evaporation operation. One simple and commonly occurring case will be considered. It may be assumed that an evaporation unit of fixed capacity is available, and a definite amount of feed and evaporation must be handled each day. The total cost for one cleaning and inventory charges are assumed to be constant no matter how much boiling time is used. The problem is to determine the cycle time which will permit operation at the least total cost.

The total cost includes (1) fixed charges on the equipment and fixed overhead expenses, (2) steam, materials, and storage costs which are proportional to the amount of feed and evaporation, (3) expenses for direct labor during the actual evaporation operation, and (4) cost of cleaning. Since the size of the equipment and the amounts of feed and evaporation are fixed, the costs included in (1) and (2) are independent of the cycle time. The optimum cycle time, therefore, can be found by minimizing the sum of the costs for cleaning and for direct labor during the evaporation.

If C_c represents the cost for one cleaning and S_b is the direct labor cost per hour during operation, the total variable costs during H hr of operating and cleaning time must be

$$C_{T,\text{for } H \text{ hr}} = (C_c + S_b\theta_b)\frac{H}{\theta_b + \theta_c} \tag{28}$$

Equations (26) and (28) may be combined to give

$$C_{T,\text{for } H \text{ hr}} = \frac{aQ_H(C_c + S_b\theta_b)}{2A\ \Delta t[(a\theta_b + d)^{1/2} - d^{1/2}]} \tag{29}$$

The optimum value of θ_b for minimum total cost may be obtained by plotting C_T versus θ_b or by setting the derivative of Eq. (29) with respect to θ_b equal to zero and solving for θ_b. The result is

$$\theta_{b,\text{per cycle for minimum total cost}} = \frac{C_c}{S_b} + \frac{2}{aS_b}\sqrt{adC_cS_b} \tag{30}$$

Equation (30) shows that the optimum cycle time is independent of the required amount of heat transfer Q_H. Therefore, a check must be made to make certain the optimum cycle time for minimum cost permits the required amount of heat transfer. This can be done easily by using the following equation, which is based on Eq. (26):

$$\theta_t = \theta_b + \theta_c = \frac{2AH'\ \Delta t}{aQ_H}[(a\theta_{b,opt} + d)^{1/2} - d^{1/2}] \tag{31}$$

where H' is the total time *available* for operation, emptying, cleaning, and recharging. If θ_t is equal to or greater than $\theta_{b,opt} + \theta_c$, the optimum boiling time indicated by Eq. (30) can be used, and the required production can be obtained at conditions of minimum cost.

The optimum cycle time determined by the preceding methods may not fit into convenient operating schedules. Fortunately, as shown in Figs. 9-3 and 9-4, the optimum points usually occur where a considerable variation in the cycle time has little effect on the factor that is being optimized. It is possible, therefore, to adjust the cycle time to fit a convenient operating schedule without causing much change in the final results.

The approach described in the preceding sections can be applied to many different types of semicontinuous cyclic operations. An illustration showing how the same reasoning is used for determining optimum cycle times in filter-press operations is presented in Example 4.

Example 4. Cycle Time for Maximum Amount of Production from a Plate-and-Frame Filter Press. Tests with a plate-and-frame filter press, operated at constant pressure, have shown that the relation between the volume of filtrate delivered and the time in operation can be represented as follows:

$$P_f^2 = 2.25 \times 10^4\,(\theta_f + 0.11)$$

where P_f = cubic feet of filtrate delivered in filtering time θ_f hr.

The cake formed in each cycle must be washed with an amount of water equal to one-sixteenth times the volume of filtrate delivered per cycle. The washing rate remains constant and is equal to one-fourth of the filtrate delivery rate at the end of the filtration. The time required per cycle for dismantling, dumping, and reassembling is 6 hr. Under the conditions where the preceding information applies, determine the total cycle time necessary to permit the maximum output of filtrate during each 24 hr.

Solution

Let θ_f = hours of filtering time per cycle

Filtrate delivered per cycle = $P_{f,\text{cycle}} = 150(\theta_f + 0.11)^{1/2}$ cu ft

Rate of filtrate delivery at end of cycle is

$$\text{Washing rate} \times 4 = \frac{dP_f}{d\theta_f} = \frac{150}{2}(\theta_f + 0.11)^{-1/2} \qquad \text{cfh}$$

$$\text{Time for washing} = \frac{\text{volume of wash water}}{\text{washing rate}}$$

$$= \frac{(4)(2)(150)(\theta_f + 0.11)^{1/2}}{(16)(150)(\theta_f + 0.11)^{-1/2}} = \frac{\theta_f + 0.11}{2} \qquad \text{hr}$$

$$\text{Total time per cycle} = \theta_f + \frac{\theta_f + 0.11}{2} + 6 = 1.5\theta_f + 6.06 \qquad \text{hr}$$

$$\text{Cycles per 24 hr} = \frac{24}{1.5\theta_f + 6.06}$$

Cu ft filtrate delivered/24 hr is

$$P_{f,\text{cycle}}\,(\text{cycles per 24 hr}) = 150(\theta_f + 0.11)^{1/2}\,\frac{24}{1.5\theta_f + 6.06}$$

At the optimum cycle time giving the maximum output of filtrate per 24 hr,

$$\frac{d(\text{cu ft filtrate delivered/24 hr})}{d\theta_f} = 0$$

Performing the differentiation and solving for θ_f,

$$\theta_{f,opt} = 3.8 \text{ hr}$$

Total cycle time necessary to permit the maximum output of filtrate = (1.5)(3.8) + 6.06 = 11.8 hr.

FLUID DYNAMICS (OPTIMUM ECONOMIC PIPE DIAMETER)

The remainder of this chapter is devoted to examples showing how optimum conditions are determined in typical chemical engineering operations. In the following example, dealing with economic pipe diameters, a detailed derivation is presented to illustrate how simplified expressions for optimum conditions can be developed.

The investment for piping and pipe fittings can amount to an important part of the total investment for a chemical plant. It is necessary, therefore, to choose pipe sizes which give close to a minimum total cost for pumping and fixed charges. For any given set of flow conditions, the use of an increased pipe diameter will cause an increase in the fixed charges for the piping system and a decrease in the pumping or blowing charges. Therefore, an optimum economic pipe diameter must exist. The value of this optimum diameter can be determined by combining the principles of fluid dynamics with cost considerations. The optimum economic pipe diameter is found at the point at which the sum of pumping or blowing costs and fixed charges based on the cost of the piping system is a minimum.

Pumping or Blowing Costs. For any given operating conditions involving the flow of a noncompressible fluid through a pipe of constant diameter, the total mechanical-energy balance can be reduced to the following form:

$$\text{Work}' = \frac{2\mathfrak{f}V^2L(1 + J)}{g_cD} + B \tag{32}$$

where Work′ = mechanical work added to system from an external mechanical source, ft-lb force/lb mass

$\mathfrak{f}$ = Fanning friction factor, dimensionless *

V = average linear velocity of fluid, fps

L = length of pipe, ft

J = frictional loss due to fittings and bends, expressed as equivalent fractional loss in a straight pipe

g_c = conversion factor in Newton's law of motion, 32.17 ft-lb mass/(sec)(sec)(lb force)

D = inside diameter of pipe, ft, subscript i means in.

B = a constant taking all other factors of the mechanical-energy balance into consideration

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* Based on Fanning equation written as Σ (friction) = $2\mathfrak{f}V^2L/g_cD$.

In the region of turbulent flow (Reynolds number greater than 2100), $\mathfrak{f}$ may be approximated for new steel pipes by the following equation:

$$\mathfrak{f} = \frac{0.04}{(N_{\mathrm{Re}})^{0.16}} \tag{33}$$

where N_{Re} is the Reynolds number or $DV\rho/\mu$.

If the flow is viscous (Reynolds number less than 2100),

$$\mathfrak{f} = \frac{16}{N_{\mathrm{Re}}} \tag{34}$$

By combining Eqs. (32) and (33) and applying the necessary conversion factors, the following equation can be obtained representing the annual pumping cost when the flow is turbulent:

$$C_{\mathrm{pumping}} = \frac{0.273 q_f^{2.84} \rho^{0.84} \mu_c^{0.16} K(1 + J) H_y}{D_i^{4.84} E} + B' \tag{35}$$

where C_{pumping} = pumping cost as dollars per year per foot of pipe length when flow is turbulent

q_f = fluid-flow rate, cfs

ρ = fluid density, lb/cu ft

μ_c = fluid viscosity, centipoises

K = cost of electrical energy, \$/kwhr

H_y = hours of operation per year

E = efficiency of motor and pump expressed as a fraction

B' = a constant independent of D_i

Similarly, Eqs. (32) and (34) and the necessary conversion factors can be combined to give the annual pumping costs when the flow is viscous:

$$C'_{\mathrm{pumping}} = \frac{0.024 q_f^{2} \mu_c K(1 + J) H_y}{D_i^{4} E} + B' \tag{36}$$

where C'_{pumping} = pumping cost as dollars per year per foot of pipe length when flow is viscous.

Equations (35) and (36) apply to noncompressible fluids. In engineering calculations, these equations are also generally accepted for gases if the total pressure drop is less than 10 per cent of the initial pressure.

Fixed Charges for Piping System. For most types of pipe, a plot of the logarithm of the pipe diameter versus the logarithm of the purchase cost per foot of pipe is essentially a straight line. Therefore, the purchase cost for pipe may be represented by the following equation:

$$c_{\mathrm{pipe}} = X D_i^{n} \tag{37}$$

where c_{pipe} = purchase cost of new pipe per foot of pipe length, \$/ft
X = purchase cost of new pipe per foot of pipe length if pipe diameter is 1 in., \$/ft
n = a constant with value dependent on type of pipe

The annual cost for the installed piping system may be expressed as follows:

$$C_{\text{pipe}} = (1 + F)XD_i^nK_F \tag{38}$$

where C_{pipe} = cost for installed piping system as dollars per year per foot of pipe length *
F = ratio of total costs for fittings and installation to purchase cost for new pipe
K_F = annual fixed charges including maintenance, expressed as a fraction of initial cost for completely installed pipe

Optimum Economic Pipe Diameter. The total annual cost for the piping system and pumping can be obtained by adding Eqs. (35) and (38) or Eqs. (36) and (38). The only variable in the resulting total-cost expressions is the pipe diameter. The optimum economic pipe diameter can be found by taking the derivative of the total annual cost with respect to pipe diameter, setting the result equal to zero, and solving for D_i. This procedure gives the following results:

For turbulent flow,

$$D_{i,opt} = \left[\frac{1.32q_f^{2.84}\rho^{0.84}\mu_c^{0.16}K(1 + J)H_y}{n(1 + F)XEK_F}\right]^{\frac{1}{4.84+n}} \tag{39}$$

For viscous flow,

$$D_{i,opt} = \left[\frac{0.096q_f^2\mu_cK(1 + J)H_y}{n(1 + F)XEK_F}\right]^{\frac{1}{4.0+n}} \tag{40}$$

The value of n for steel pipes is approximately 1.5 if the pipe diameter is 1 in. or larger and 1.0 if the diameter is less than 1 in. Substituting these values in Eqs. (39) and (40) gives:

For turbulent flow in steel pipes,

$D_i \geqq 1$ in.:

$$D_{i,opt} = q_f^{0.448}\rho^{0.132}\mu_c^{0.025}\left[\frac{0.88K(1 + J)H_y}{(1 + F)XEK_F}\right]^{0.158} \tag{41}$$

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* Pump cost could be included if desired; however, in this analysis, the cost of the pump is considered as essentially invariant with pipe diameter.

$D_i < 1$ in.:

$$D_{i,opt} = q_f^{0.487}\rho^{0.144}\mu_c^{0.027}\left[\frac{1.32K(1+J)H_y}{(1+F)XEK_F}\right]^{0.171} \tag{42}$$

For viscous flow in steel pipes,

$D_i \geqq 1$ in.:

$$D_{i,opt} = q_f^{0.364}\mu_c^{0.182}\left[\frac{0.064K(1+J)H_y}{(1+F)XEK_F}\right]^{0.182} \tag{43}$$

$D_i < 1$ in.:

$$D_{i,opt} = q_f^{0.40}\mu_c^{0.20}\left[\frac{0.096K(1+J)H_y}{(1+F)XEK_F}\right]^{0.20} \tag{44}$$

The exponents involved in Eqs. (41) through (44) indicate that the optimum diameter is relatively insensitive to most of the terms involved. Since the exponent on the viscosity term in Eqs. (41) and (42) is very small, the value of $\mu_c^{0.025}$ and $\mu_c^{0.027}$ may be taken as unity over a viscosity range of 0.02 to 20 centipoises. It is possible to simplify the equations further by substituting average numerical values for some of the less critical terms. The following values are applicable under ordinary industrial conditions:

K = \$0.011/kwhr
J = 0.35 or 35 per cent
H_y = 8760 hr/year
E = 0.40 or 40 per cent
F = 1.4
K_F = 0.14 or 14 per cent
X = \$0.16 per foot for 1-in.-diameter steel pipe

Substituting these values into Eqs. (41) through (44) gives the following simplified results:*†

For turbulent flow in steel pipes,

$D_i \geqq 1$ in.:

$$D_{i,opt} = 3.9q_f^{0.45}\rho^{0.13} = \frac{2.2w_m^{0.45}}{\rho^{0.32}} \tag{45}$$

where w_m = thousands of pounds mass flowing per hour.

$D_i < 1$ in.:

$$D_{i,opt} = 4.7q_f^{0.49}\rho^{0.14} \tag{46}$$

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* R. P. Genereaux, *Ind. Eng. Chem.*, **29**:385 (1937).

† B. R. Sarchet and A. P. Colburn, *Ind. Eng. Chem.*, **32**:1249 (1940).

For viscous flow in steel pipes,

$D_i \geqq 1$ in.:

$$D_{i,opt} = 3.0q_f^{0.36}\mu_c^{0.18} \tag{47}$$

$D_i < 1$ in.:

$$D_{i,opt} = 3.6q_f^{0.40}\mu_c^{0.20} \tag{48}$$

Depending on the accuracy desired and the type of flow, Eqs. (39) through (48) may be used to determine optimum economic pipe diameters. Equations (45) through (48) are sufficiently accurate for design estimates under ordinary plant conditions, and a nomograph based on these equations is presented in Chap. 14 (Materials Handling and Transfer Equipment—Design and Costs).*

HEAT TRANSFER (OPTIMUM FLOW RATE OF COOLING WATER IN CONDENSER)

If a condenser, with water as the cooling medium, is designed to carry out a given duty, the cooling water may be circulated at a high rate with a small change in water temperature or at a low rate with a large change in water temperature. The temperature of the water affects the temperature-difference driving force for heat transfer. Use of an increased amount of water, therefore, will cause a reduction in the necessary amount of heat-transfer area and a resultant decrease in the original investment and fixed charges. On the other hand, the cost for the water will increase if more water is used. An economic balance between conditions of high water rate–low surface area and low water rate–high surface area indicates that the optimum flow rate of cooling water occurs at the point of minimum total cost for cooling water and equipment fixed charges.

Consider the general case in which heat must be removed from a condensing vapor at a given rate designated by q Btu/hr. The vapor condenses at a constant temperature of t'°F, and cooling water is supplied at a temperature of t_1°F. The following additional notation applies:

w = flow rate of cooling water, lb/hr
c_p = heat capacity of cooling water, Btu/(lb)(°F)
t_2 = temperature of cooling water leaving condenser, °F
U = constant over-all coefficient of heat transfer determined at optimum conditions, Btu/(hr)(sq ft)(°F)
A = area of heat transfer, sq ft

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* Other methods for determining optimum economic pipe diameters are discussed by W. H. Stanton, *Ind. Eng. Chem.*, **42**:87A (October, 1950); G. F. Downs, Jr., and G. R. Tait, *Oil Gas J.*, **52**(28):210 (1953); and R. M. Braca and J. Happel, *Chem. Eng.*, **60**(1):180 (1953).

$\Delta t_{l.m.}$ = log-mean temperature-difference driving force over condenser, °F
H_y = hours the condenser is operated per year, hr/year
C_w = cooling-water cost assumed as directly proportional to amount of water supplied,* \$/lb
C_A = installed cost of heat exchanger per square foot of heat-transfer area, \$/sq ft
K_F = annual fixed charges including maintenance, expressed as a fraction of initial cost for completely installed equipment

The rate of heat transfer as Btu per hour can be expressed as

$$q = wc_p(t_2 - t_1) = UA\ \Delta t_{l.m.} = \frac{UA(t_2 - t_1)}{\ln [(t' - t_1)/(t' - t_2)]} \tag{49}$$

Solving for w,

$$w = \frac{q}{c_p(t_2 - t_1)} \tag{50}$$

The design conditions set the values of q and t_1, and the heat capacity of water may ordinarily be approximated as 1 Btu (lb)(°F). Therefore, Eq. (50) shows that the flow rate of the cooling water is fixed if the temperature of the water leaving the condenser (t_2) is fixed. Under these conditions, the optimum flow rate of cooling water can be found directly from the optimum value of t_2.

The annual cost for cooling water is wH_yC_w. From Eq. (50),

$$wH_yC_w = \frac{qH_yC_w}{c_p(t_2 - t_1)} \tag{51}$$

The annual fixed charges for the condenser are AK_FC_A, and the total annual cost for cooling water plus fixed charges is

$$\text{Total annual variable cost} = \frac{qH_yC_w}{c_p(t_2 - t_1)} + AK_FC_A \tag{52}$$

Substituting for A from Eq. (49),

$$\text{Total annual variable cost} = \frac{qH_yC_w}{c_p(t_2 - t_1)} + \frac{qK_FC_A \ln [(t' - t_1)/(t' - t_2)]}{U(t_2 - t_1)} \tag{53}$$

---

* Cooling water is assumed to be available at a pressure sufficient to handle any pressure drop in the condenser; therefore, any cost due to pumping the water is included in C_w.

The only variable in Eq. (53) is the temperature of the cooling water leaving the condenser. The optimum cooling-water rate occurs when the total annual cost is a minimum. Thus, the corresponding optimum exit temperature can be found by differentiating Eq. (53) with respect to t_2 (or, more simply, with respect to $t' - t_2$) and setting the result equal to zero. When this is done, the following equation is obtained:

$$\frac{t' - t_1}{t' - t_{2,opt}} - 1 + \ln \frac{t' - t_{2,opt}}{t' - t_1} = \frac{UH_yC_w}{K_Fc_pC_A} \tag{54}$$

The optimum value of t_2 can be found from Eq. (54) by a trial-and-error solution, and Eq. (50) can then be used to determine the optimum flow rate of cooling water. The trial-and-error solution can be eliminated by use of Fig. 9-5, which is a plot of Eq. (54).*

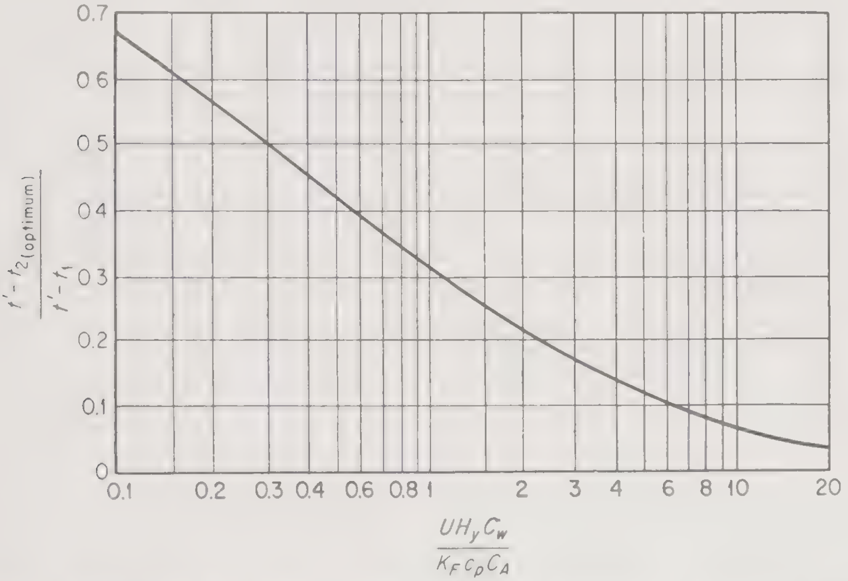

Fig. 9-5. Solution of Eq. (54) for use in evaluating optimum flow rate of cooling medium in condenser.

Example 5. Optimum Cooling-water Flow Rate in Condenser. A condenser for a distillation unit must be designed to condense 5000 lb of vapor per hour. The effective condensation temperature for the vapor is 170°F. The heat of condensation for the vapor is 200 Btu/lb. Cooling water is available at 70°F. The cost of the cooling water is \$0.02 per 1000 gal. The over-all heat-transfer coefficient at the optimum conditions may be taken as 50 Btu/(hr)(sq ft)(°F). The cost for the installed heat exchanger is \$7 per square foot of heat-transfer area, and annual fixed charges including maintenance are 20 per cent of the initial investment. The heat capacity of the water may be assumed to be constant at 1.0 Btu/(lb)(°F). If the condenser is to operate 6000 hr/year, determine the cooling-water flow rate in pounds per hour for optimum economic conditions.

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* See Fig. 15-18 for a similar plot for counterflow coolers.

Solution

$U = 50$ Btu/(hr)(sq ft)(°F)
$H_y = 6000$ hr/year
$K_F = 0.20$
$c_p = 1.0$ Btu/(lb)(°F)
$C_A = \$7.0$/sq ft

$$C_w = \frac{0.02}{(1000)(8.33)} = \$0.0000024/\text{lb}$$

$$\frac{UH_yC_w}{K_Fc_pC_A} = \frac{(50)(6000)(0.0000024)}{(0.20)(1.0)(7.0)} = 0.515$$

The optimum exit temperature may be obtained by a trial-and-error solution of Eq. (54) or by use of Fig. 9-5.

From Fig. 9-5, when the abscissa is 0.515,

$$\frac{t' - t_{2,opt}}{t' - t_1} = 0.42$$

where $t' = 170$°F
$t_1 = 70$°F
$t_{2,opt} = 128$°F

By Eq. (50), at the optimum economic conditions,

$$w = \frac{q}{c_p(t_2 - t_1)} = \frac{(5000)(200)}{(1.0)(128 - 70)} = 17{,}200 \text{ lb water/hr}$$

MASS TRANSFER (OPTIMUM REFLUX RATIO)

The design of a distillation unit is ordinarily based on specifications giving the degree of separation required for a feed supplied to the unit at a known composition, temperature, and flow rate. The design engineer must determine the size of column and reflux ratio necessary to meet the specifications. As the reflux ratio is increased, the number of theoretical stages required for the given separation decreases. An increase in reflux ratio, therefore, may result in lower fixed charges for the distillation column and greater costs for the reboiler heat supply and condenser coolant.

As indicated in Fig. 9-6, the optimum reflux ratio occurs at the point where the sum of fixed charges and operating costs is a minimum. As a rough approximation, the optimum reflux ratio usually falls in the range of 1.1 to 1.5 times the minimum reflux ratio. The following example illustrates the general method for determining the optimum reflux ratio in distillation operations.

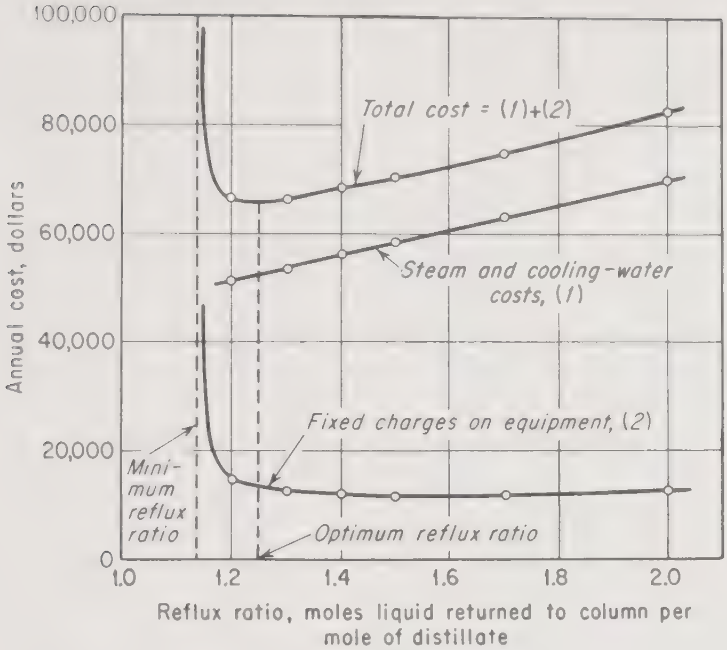

FIG. 9-6. Optimum reflux ratio in distillation operation.

Example 6. Determination of Optimum Reflux Ratio. A bubble-cap distillation column is being designed to handle 700 lb mole of feed per hour. The unit is to operate continuously at a total pressure of 1 atm. The feed contains 45 mole % benzene and 55 mole % toluene, and the feed enters at its boiling temperature. The overhead product from the distillation tower must contain 92 mole % benzene, and the bottoms must contain 95 mole % toluene. Determine the following:

(*a*) The optimum reflux ratio as moles liquid returned to tower per mole of distillate product withdrawn.

(*b*) The ratio of the optimum reflux ratio to the minimum reflux ratio.

(*c*) The per cent of the total variable cost due to steam consumption at the optimum conditions.

The following data apply:

Vapor-liquid equilibrium data for benzene-toluene mixtures at atmospheric pressure are presented in Fig. 9-7.

The molal heat capacity for liquid mixtures of benzene and toluene in all proportions may be assumed to be 40 Btu/(lb mole)(°F).

The molal heat of vaporization of benzene and toluene may be taken as 13,700 Btu/lb mole.

Effects of change in temperature on heat capacity and heats of vaporization are negligible. Heat losses from the column are negligible. Effects of pressure drop over the column may be neglected.

The over-all coefficient of heat transfer is 80 Btu/(hr)(sq ft)(°F) in the reboiler and 100 Btu/(hr)(sq ft)(°F) in the condenser.

The boiling temperature is 201°F for the feed, 179°F for the distillate, and 227°F for the bottoms. The temperature-difference driving force in the reflux condenser may be based on an average cooling-water temperature of 90°F, and the change in cooling-water

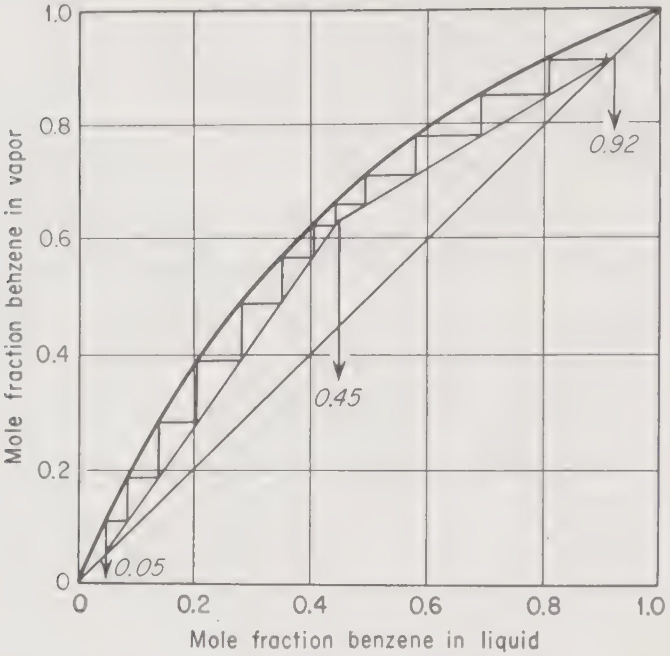

FIG. 9-7. Equilibrium diagram for benzene-toluene mixtures at total pressure of 760 mm Hg (McCabe-Thiele method for determining number of theoretical stages).

temperature is 50°F for all cases. Saturated steam at 60 psia is used in the reboiler. At this pressure, the temperature of the condensing steam is 292.7°F and the heat of condensation is 915.5 Btu/lb. No heat-saving devices are used.

The column diameter is to be based on a maximum allowable vapor velocity of 2.5 fps at the top of the column. The over-all plate efficiency may be assumed to be 70 per cent. The unit is to operate 8500 hr per year.

COST DATA:

Steam = $0.50/1000 lb.

Cooling water = $0.03/1000 gal or $0.036/10,000 lb.

The sum of costs for piping, insulation, and instrumentation can be estimated to be 60 per cent of the cost for the installed equipment. Annual fixed charges amount to 15 per cent of the total cost for installed equipment, piping, instrumentation, and insulation.

The following costs are for the installed equipment and include delivery and erection costs:

BUBBLE-CAP DISTILLATION COLUMN
Values may be interpolated

Diameter, in.	*$/plate*
60	800
70	1000
80	1230
90	1500
100	1800

CONDENSER—TUBE-AND-SHELL HEAT EXCHANGER

Values may be interpolated

Heat-transfer area, sq ft	$
800	6500
1000	7500
1200	8400
1400	9200
1600	9900

REBOILER—TUBE-AND-SHELL HEAT EXCHANGER

Values may be interpolated

Heat-transfer area, sq ft	$
1000	11,500
1400	14,100
1800	16,400
2200	18,500
2600	20,200

Solution

The variable costs involved are cost of column, cost of reboiler, cost of condenser, cost of steam, and cost of cooling water. Each of these costs is a function of the reflux ratio, and the optimum reflux ratio occurs at the point where the sum of the annual variable costs is a minimum. The total variable cost will be determined at various reflux ratios, and the optimum reflux ratio will be found by the graphical method.

Sample calculation for reflux ratio = 1.5:

ANNUAL COST FOR DISTILLATION COLUMN. The McCabe-Thiele simplifying assumptions apply for this case, and the number of theoretical plates can be determined by the standard graphical method shown in Fig. 9-7. The slope of the enriching operating line is 1.5 (1.5 + 1) = 0.6. From Fig. 9-7, the total number of theoretical stages required for the given separation is 12.1.

The actual number of plates = (12.1 − 1)/0.70 = 16.

The moles of distillate per hour (M_D) and the moles of bottoms per hour (M_B) may be determined by a benzene material balance as follows:

$$(700)(0.45) = (M_D)(0.92) + (700 - M_D)(0.05)$$

$$M_D = 322 \text{ moles distillate/hr}$$

$$M_B = 700 - 322 = 378 \text{ moles bottoms/hr}$$

Moles vapor per hour at top of column = 322(1 + 1.5) = 805.

Applying the perfect-gas law,

$$\text{Vapor velocity at top of tower} = 2.5 \text{ fps} = \frac{(805)(359)(460 + 179)(4)}{(3600)(492)(\pi)(\text{diameter})^2}$$

$$\text{Diameter} = 7.3 \text{ ft}$$

$$\text{Cost per plate} = \$1430$$

$$\text{Annual cost for distillation column} = (1430)(16)(1 + 0.60)(0.15) = \$5490$$

ANNUAL COST FOR CONDENSER. Rate of heat transfer per hour in condenser = (moles vapor condensed per hour)(molal latent heat of condensation) = (805)(13,700) = 11,000,000 Btu/hr.

From the basic heat-transfer-rate equation $q = UA\,\Delta t$,

$$A = \text{heat-transfer area} = \frac{(11{,}000{,}000)}{(100)(179 - 90)} = 1240 \text{ sq ft}$$

$$\text{Cost per square foot} = \frac{\$8550}{1240}$$

$$\text{Annual cost for condenser} = \frac{8550}{1240}(1240)(1 + 0.60)(0.15)$$

$$= \$2050$$

ANNUAL COST FOR REBOILER. The rate of heat transfer in the reboiler (q_r) can be determined by a total energy balance around the distillation unit.

Base energy level on liquid at 179°F.

$$\text{Heat input} = \text{heat output}$$

$$q_r + (700)(201 - 179)(40) = 11{,}000{,}000 + (378)(227 - 179)(40)$$

$$q_r = 11{,}110{,}000 \text{ Btu/hr} = UA\,\Delta t$$

$$A = \text{heat-transfer area} = \frac{11{,}110{,}000}{(80)(292.7 - 227)} = 2120 \text{ sq ft}$$

$$\text{Cost per square foot} = \frac{\$18{,}100}{2120}$$

$$\text{Annual cost for reboiler} = \frac{18{,}100}{2120}(2120)(1 + 0.60)(0.15)$$

$$= \$4340$$

ANNUAL COST FOR COOLING WATER. The rate of heat transfer in the condenser = 11,000,000 Btu/hr. The heat capacity of water may be taken as 1.0 Btu/(lb)(°F).

$$\text{Annual cost for cooling water} = \frac{(11{,}000{,}000)(0.036)(8500)}{(1.0)(50)(10{,}000)}$$

$$= \$6740$$

ANNUAL COST FOR STEAM. The rate of heat transfer in the reboiler = 11,110,000 Btu/hr.

$$\text{Annual cost for steam} = \frac{(11{,}110{,}000)(0.50)(8500)}{(915.5)(1000)}$$

$$= \$51{,}700$$

TOTAL ANNUAL VARIABLE COST AT REFLUX RATIO OF 1.5

$$\$5490 + \$2050 + \$4340 + \$6740 + \$51{,}700 = \$70{,}320$$

By repeating the preceding calculations for different reflux ratios, the following table can be prepared:

Reflux ratio	Number of actual plates required	Column diameter, ft	Annual cost, dollars, for					Total annual cost, dollars
			Column	Condenser	Reboiler	Cooling water	Steam	
1.14	α	6.7	α	1870	3960	5780	44,300	α
1.2	29	6.8	8930	1910	4040	5940	45,500	66,320
1.3	21	7.0	6620	1950	4130	6200	47,500	66,400
1.4	18	7.1	5920	2000	4240	6470	49,600	68,230
1.5	16	7.3	5490	2050	4340	6740	51,700	70,320
1.7	14	7.7	5290	2150	4540	7290	55,700	74,970
2.0	13	8.0	5210	2280	4800	8100	61,800	82,190

(*a*) The data presented in the preceding table are plotted in Fig. 9-6. The minimum total cost per year occurs at a reflux ratio of 1.25.

$$\text{Optimum reflux ratio} = 1.25$$

(*b*) For conditions of minimum reflux ratio, the slope of the enriching line in Fig. 9-7 is 0.532

$$\frac{\text{Minimum reflux ratio}}{\text{Minimum reflux ratio} + 1} = 0.532$$

$$\text{Minimum reflux ratio} = 1.14$$

$$\frac{\text{Optimum reflux ratio}}{\text{Minimum reflux ratio}} = \frac{1.25}{1.14} = 1.1$$

(*c*) At the optimum conditions,

$$\text{Annual steam cost} = \$46{,}500$$

$$\text{Total annual variable cost} = \$66{,}000$$

$$\text{Per cent of variable cost due to steam consumption} = \frac{46{,}500}{66{,}000}(100) = 70\%$$

NOMENCLATURE FOR CHAP. 9

a = constant
A = heat-transfer area, sq ft
b = constant
B = constant
B' = constant
c = constant

c_p = heat capacity, Btu/(lb)(°F)
c_{pipe} = purchase cost of new pipe per foot of pipe length, \$/ft
c_T = total cost per unit of production, \$/unit of production
C_A = installed cost of heat exchanger per square foot of heat-transfer area, \$/sq ft
C_c = cost for one cleaning, dollars
C_F = fixed costs, \$/year
C_{pipe} = installed cost for piping system expressed as dollars per year per foot of pipe length, \$/(year)(ft)
C_{pumping} = pumping costs as dollars per year per foot of pipe length when flow is turbulent, \$/(year)(ft)
C'_{pumping} = pumping cost as dollars per year per foot of pipe length when flow is viscous, \$/(year)(ft)
C_T = total cost for a given unit of time, dollars
C_w = cost of cooling water, \$/lb
d = constant
D = inside diameter of pipe, ft
D_i = inside diameter of pipe, in.
E = efficiency of motor and pump expressed as a fraction
f = Fanning friction factor, dimensionless
F = ratio of total cost for fittings and installation to purchase cost for new pipe
g_c = conversion factor in Newton's law of motion, 32.17 ft-lb mass/(sec)(sec)(lb force)
h = operating costs which remain constant per unit of production, \$/unit of production
H = total time used for actual operation, emptying, cleaning, and recharging, hr
H' = total time available for operation, emptying, cleaning, and recharging, hr
H_y = total time of operation per year, hr/year
J = frictional loss due to fittings and bends, expressed as equivalent fractional loss in a straight pipe
K = cost of electrical energy, \$/kwhr
K_F = annual fixed charges including maintenance, expressed as a fraction of the initial cost for the completely installed equipment
L = length of pipe, ft
m = constant
M_B = bottoms flow rate, moles/hr
M_D = distillate flow rate, moles/hr
n = constant
N_{Re} = Reynolds number = $DV\rho/\mu$, dimensionless
O_c = organization costs per unit of time, \$/day
P = rate of production, units of production/day
P_b = amount of production per batch, lb/batch
P_f = filtrate delivered in filtering time θ_f hr, cu ft
P_o = optimum rate of production, units of production/day
q = rate of heat transfer, Btu/hr
q_f = rate of fluid flow, cfs
q_r = rate of heat transfer in reboiler, Btu/hr
Q = total amount of heat transferred in a given time, Btu
Q_H = total amount of heat transferred in H hr, Btu
r = profit per unit of production, \$/unit of production
R = profit per unit of time, \$/day
s = selling price per unit of production, \$/unit of production

S_b = direct labor cost per hour during operation, \$/hr
t = temperature, °F
t_1 = temperature of cooling water entering condenser, °F
t_2 = temperature of cooling water leaving condenser, °F
t' = condensation temperature, °F
U = over-all coefficient of heat transfer, Btu/(hr)(sq ft)(°F)
V = average linear velocity, fps
w = flow rate, lb/hr
w_m = thousands of pounds mass flowing per hour, 1000 lb/hr
x = a variable
X = purchase cost for new pipe per foot of pipe length if pipe diameter is 1 in., \$/ft
y = a variable
z = a variable

Greek Symbols

Δt = delta t, temperature-difference driving force (subscript *l.m.* designates log mean) °F
θ_b = theta, time in operation, hr or hr/cycle
θ_c = time for emptying, cleaning, and recharging per cycle, hr/cycle
θ_f = filtering time, hr or hr/cycle
θ_t = total time per complete cycle, hr/cycle
μ = mu, absolute viscosity, lb mass/(sec)(ft)
μ_c = absolute viscosity, centipoises
ρ = rho, density, lb mass/cu ft
$\phi, \phi^i, \phi^{ii}, \phi^{iii}$ = phi, function of the indicated variables

PROBLEMS

1. A multiple-effect evaporator is to be used for evaporating 400,000 lb of water per day from a salt solution. The total initial cost for the first effect is \$18,000, and each additional effect costs \$15,000. The life period is estimated to be 10 years, and the salvage or scrap value at the end of the life period may be assumed to be zero. The straight-line depreciation method is used. Fixed charges minus depreciation are 15 per cent yearly based on the first cost of the equipment. Steam costs \$0.50 per 1000 lb. Annual maintenance charges are 5 per cent of the initial equipment cost. All other costs are independent of the number of effects. The unit will operate 300 days per year. If the pounds of water evaporated per pound of steam equals 0.85 × number of effects, determine the optimum number of effects for minimum annual cost.

2. Determine the optimum economic thickness of insulation that should be used under the following conditions: Saturated steam is being passed continuously through a steel pipe with an outside diameter of 10.75 in. The temperature of the steam is 400°F, and the steam is valued at \$0.60 per 1000 lb. The pipe is to be insulated with a material that has a thermal conductivity of 0.03 Btu/(hr)(sq ft)(°F/ft). The cost of the installed insulation per foot of pipe length is \$4.5 × I_t, where I_t is the thickness of the insulation in inches. Annual fixed charges including maintenance amount to 20 per cent of the initial installed cost. The total length of the pipe is 1000 ft, and the average temperature of the surroundings may be taken as 70°F. Heat-transfer resistances due to the steam film, scale, and pipe wall are negligible. The air-film coefficient at the outside of the insulation may be assumed constant at 2.0 Btu/(hr)(sq ft)(°F) for all insulation thicknesses.

3. An absorption tower containing wooden grids is to be used for absorbing SO_2 in a sodium sulfite solution. A mixture of air and SO_2 will enter the tower at a rate of 70,000 cfm, temperature of 250°F, and pressure of 1.1 atm. The concentration of SO_2 in the entering gas is specified, and a given fraction of the entering SO_2 must be removed in the absorption tower. The molecular weight of the entering gas mixture may be assumed to be 29.1. Under the specified design conditions, the number of transfer units necessary varies with the superficial gas velocity as follows:

$$\text{Number of transfer units} = 0.32G_s^{0.18}$$

where G_s is the entering gas velocity as lb/(hr)(sq ft) based on the cross-sectional area of the empty tower. The height of a transfer unit is constant at 15 ft. The cost for the installed tower is \$1 per cubic foot of inside volume, and annual fixed charges amount to 20 per cent of the initial cost. Variable operating charges for the absorbent, blower power, and pumping power are represented by the following equation:

$$\text{Total variable operating costs as \$/hr} = 1.8G_s^2 \times 10^{-8} + \frac{81}{G_s} + \frac{4.8}{G_s^{0.8}}$$

The unit is to operate 8000 hr/year. Determine the height and diameter of the absorption tower at conditions of minimum annual cost.

4. Derive an expression for the optimum economic thickness of insulation to put on a flat surface if the annual fixed charges per square foot of insulation are directly proportional to the thickness, (*a*) neglecting the air film, (*b*) including the air film. The air-film coefficient of heat transfer may be assumed as constant for all insulation thicknesses.

5. A continuous evaporator is operated with a given feed material under conditions in which the concentration of the product remains constant. The feed rate at the start of a cycle after the tubes have been cleaned has been found to be 10,000 lb/hr. After 48 hr of continuous operation, tests have shown that the feed rate decreases to 5000 lb/hr. The reduction in capacity is due to true scale formation. If the down time per cycle for emptying, cleaning, and recharging is 6 hr, how long should the evaporator be operated between cleanings in order to obtain the maximum amount of product per 30 days?

6. A solvent-extraction operation is carried out continuously in a plate column with gravity flow. The unit is operated 24 hr/day. A feed rate of 1500 cu ft/day must be handled 300 days per year. The allowable velocity per square foot of cross-sectional tower area is 40 cu ft of combined solvent and charge per hour. The annual fixed costs for the installation can be predicted from the following equation:

$$C_F = 8800F_{sf}^2 - 51{,}000F_{sf} + 110{,}000 \qquad \$/\text{year}$$

where F_{sf} = cubic feet of solvent per cubic foot of feed. Operating and other variable costs depend on the amount of solvent that must be recovered, and these costs are \$0.04 for each cubic foot of solvent passing through the tower. What tower diameter should be used for optimum conditions of minimum total cost per year?

7. Prepare a plot of optimum economic pipe diameter versus the flow rate of fluid in the pipe under the following conditions:

Costs and operating conditions ordinarily applicable in industry may be used.

The flow of the fluid may be considered as in the turbulent range.

The viscosity of the fluid may range from 0.1 to 20 centipoises.

The plot is to apply for steel pipe.

Express the diameters in inches and use inside diameters.

The plot should cover a diameter range of 0.1 to 100 in.

Express the flow rate in 1000 lb/hr.

The plot should cover a flow-rate range of 10 to 100,000 lb/hr.

The plot should be presented on log-log coordinates.

One line on the plot should be presented for each of the following fluid densities: 100, 50, 10, 1, 0.1, 0.01, and 0.001 lb/cu ft.

8. For the conditions indicated in Prob. 7, prepare a log-log plot of fluid velocity in feet per second versus optimum economic pipe diameter in inches. The plot should cover a fluid-velocity range of 1 to 100 fps and a pipe-diameter range of 1 to 10 in.

9. A continuous evaporator is being used to concentrate a scale-forming solution of sodium sulfate in water. The over-all coefficient of heat transfer decreases according to the following expression:

$$\frac{1}{U^2} = 8 \times 10^{-6}\theta_b + 6 \times 10^{-6}$$

where U = over-all coefficient of heat transfer, Btu/(hr)(sq ft)(°F), and θ_b = time in operation, hr.

The only factor which affects the over-all coefficient is the scale formation. The liquid enters the evaporator at the boiling point, and the temperature and heat of vaporization are constant. At the operating conditions, 990 Btu are required to vaporize 1 lb of water, the heat-transfer area is 400 sq ft, and the temperature-difference driving force is 70°F. The time required to shut down, clean, and get back on stream is 4 hr for each shutdown, and the total cost for this cleaning operation is \$100 per cycle. The labor costs during operation of the evaporator are \$10 per hour. Determine the total time per cycle for minimum total cost under the following conditions:

(*a*) An over-all average of 65,000 lb of water per 24-hr day must be evaporated during each 30-day period.

(*b*) An over-all average of 81,000 lb of water per 24-hr day must be evaporated during each 30-day period.

10. An organic chemical is produced by a batch process. In this process, chemicals X and Y react to form chemical Z. Since the reaction rate is very high, the total time required per batch has been found to be independent of the amounts of the materials, and each batch requires 2 hr, including time for charging, heating, and dumping. The following equation shows the relation between the pounds of Z produced (lb_Z) and the pounds of X (lb_X) and Y (lb_Y) supplied:

$$\text{lb}_Z = 1.5(1.1\ \text{lb}_X\ \text{lb}_Z + 1.3\ \text{lb}_Y\ \text{lb}_Z - \text{lb}_X\ \text{lb}_Y)^{0.5}$$

Chemical X costs \$0.09 per pound. Chemical Y costs \$0.04 per pound. Chemical Z sells for \$0.80 per pound. If one-half of the selling price for chemical Z is due to costs other than for raw materials, what is the maximum profit obtainable per pound of chemical Z?

11. Derive an expression similar to Eq. (54) (Chap. 9) for finding the optimum exit temperature of cooling water from a heat exchanger when the temperature of the material being cooled is not constant. Designate the true temperature-difference driving force by $F_G\,\Delta t_{l\,m}$, where F_G is a correction factor with value dependent on the geometrical arrangement of the passes in the exchanger. Use primes to designate the temperature of the material that is being cooled.

12. Under the following conditions, determine the optimum economic thickness of insulation for a $1\frac{1}{2}$-in. standard pipe carrying saturated steam at 100 psig. The line is in use continuously. The covering specified is light carbonate magnesia, which is marketed in whole-number thicknesses only (i.e., 1 in., 2 in., 3 in., etc.). The cost of the installed insulation may be approximated as $10 per cubic foot of insulation. Annual fixed charges are 20 per cent of the initial investment, and the heat of the steam is valued at $0.75 per 1 million Btu. The temperature of the surroundings may be assumed to be 80°F.

L. B. McMillan, *Trans. ASME*, **48**:1269 (1926), has presented approximate values of optimum economic insulation thickness versus the group $(kb_cH_y\,\Delta t/a_c)^{0.5}$, with pipe size as a parameter.

k = thermal conductivity of insulation, Btu/(hr)(sq ft)(°F/ft)
b_c = cost of heat, $/Btu
H_y = hours of operation per year, hr/year
Δt = over-all temperature-difference driving force, °F
a_c = cost of insulation, $/(cu ft)(year)

The following data are based on the results of McMillan, and these data are applicable to the conditions of this problem:

$\left(\dfrac{kb_cH_y\,\Delta t}{a_c}\right)^{0.5}$	Optimum economic thickness of insulation, in., for nominal pipe diameter of			
	½ in.	1 in.	2 in.	4 in.
0.1	....	0.40	0.5	0.6
0.2	0.80	0.95	1.1	1.3
0.3	1.20	1.4	1.6	1.9
0.5	1.85	2.1	2.45	2.9
0.8	2.75	3.1	3.6	4.3
1.2	3.80	4.3	4.9	

13. A catalytic process uses a catalyst which must be regenerated periodically because of reduction in conversion efficiency. The cost for one regeneration is constant at $800. This figure includes all shutdown and start-up cost, as well as the cost for the actual regeneration. The feed rate to the reactor is maintained constant at 150 lb/day, and the cost for the feed material is $2.50 per pound. The daily costs for operation are $300, and fixed charges plus general overhead costs are $100,000 per year. Tests on the catalyst show that the yield of product as pounds of product per pound of feed during the first day of operation with the regenerated catalyst is 0.87, and the yield decreases as $0.87/(\theta_D)^{0.25}$, where θ_D is the time in operation expressed in days. The time necessary to shut down the unit, replace the catalyst, and start up the unit is negligible. The value of the product is $14.00 per pound, and the plant operates 300 days per year. Assuming no costs are involved other than those mentioned, what is the maximum annual profit that can be obtained under these conditions?

CHAPTER 10

GENERAL DESIGN CONSIDERATIONS

The development of a complete plant design requires consideration of many different subjects. As indicated in the preceding chapters, the role of costs and profits is very important. The application of engineering principles in the design of individual pieces of equipment is equally important. In addition, many other factors must be considered, such as plant location, plant layout, plant operation and control, patent and legal restrictions, structural design, and marketing of finished products.

The design engineer cannot be an expert on each of the many functions that are part of the detailed passage from an initial idea to a complete industrial plant. He should, however, recognize the importance of the different factors and understand their role in the total project.

This chapter presents an over-all view of the various functions involved in the development of a complete plant design. Particular emphasis is placed on the general considerations which serve to integrate the design and yield a successful final plant.

Types of Designs. The methods for carrying out a design project may be divided into the following classifications, depending on the accuracy and detail required:

1. Preliminary or quick-estimate designs
2. Detailed-estimate designs
3. Firm process designs

Preliminary designs are ordinarily used as a basis for determining whether further work should be done on the proposed process. The design is based on approximate process methods, and rough cost estimates are prepared. Few details are included, and the time spent on calculations is kept at a minimum.

If the results of the preliminary design show that further work is justified, a *detailed-estimate design* may be developed. In this type of design, the cost-and-profit potential of an established process is determined by detailed analyses and calculations. However, exact specifications are not given for the equipment, and drafting-room work is minimized.

When the detailed-estimate design indicates that the proposed project should be a commercial success, the final step before developing construction plans for the plant is the preparation of a *firm process design*. Complete specifications are presented for all components of the plant, and accurate costs based on quoted prices are obtained. The firm process design includes blueprints and sufficient information to permit immediate development of the final plans for constructing the plant.

DESIGN-PROJECT PROCEDURE

The development of a design project always starts with an initial idea or plan. This initial idea must be stated as clearly and concisely as possible in order to define the scope of the project. General specifications and pertinent laboratory or chemical engineering data should be presented along with the initial idea.

Feasibility Survey. Before any detailed work is done on the design, the technical and economic factors of the proposed process should be examined. The various reactions and physical processes involved must be considered, along with the existing and potential market conditions for the particular product. A preliminary feasibility survey of this type gives an immediate indication of the probable success of the project and also shows what additional information is necessary to make a complete evaluation. Following is a list of items that should be considered in making a feasibility survey:

1. Raw materials (availability, quantity, quality, cost)
2. Thermodynamics and kinetics of chemical reactions involved (equilibrium, yields, rates, optimum conditions)
3. Facilities and equipment available at present
4. Facilities and equipment which must be purchased
5. Estimation of production costs and total investment
6. Profits (probable and optimum, per pound of product and per year, return on investment)
7. Materials of construction
8. Safety considerations
9. Markets (present and future supply and demand, present uses, new uses, present buying habits, price range for products and by-products, character, location, and number of possible customers)
10. Competition (over-all production statistics, comparison of various manufacturing processes, product specifications of competitors)
11. Properties of products (chemical and physical properties, specifications, impurities, effects of storage)
12. Sales and sales service (method of selling and distributing, advertising required, technical services required)
13. Shipping restrictions and containers

14. Plant location
15. Patent situation and legal restrictions

When detailed data on the process and firm product specifications are available, a complete market analysis combined with a consideration of all sales factors should be made. This analysis can be based on a breakdown of items 9 through 15 as indicated in the preceding list.

Process Development. In many cases, the preliminary feasibility survey indicates that additional research, laboratory, or pilot-plant data are necessary, and a program to obtain this information may be initiated. Process development on a pilot-plant or semiworks scale is usually desirable in order to get accurate design data. Valuable information on material and energy balances can be obtained, and process conditions can be examined to supply data on temperature and pressure variations, yields, rates, grades of raw materials and products, batch versus continuous operation, materials of construction, operating characteristics, and other pertinent design variables.

Design. If sufficient information is available, a preliminary design may be developed in conjunction with the preliminary feasibility survey. When essential data are not available until provided through process development, the preliminary design should be carried out as soon as the necessary information is obtained. In this way, the preliminary design can serve its function of eliminating an undesirable project before a large amount of time and money is expended.

The preliminary design and the process-development work give the results necessary for a detailed-estimate design. The following factors should be established within narrow limits before a detailed-estimate design is developed:

1. Manufacturing process
2. Material and energy balances
3. Temperature and pressure ranges
4. Raw-material and product specifications
5. Yields, reaction rates, and time cycles
6. Materials of construction
7. Utilities requirements
8. Plant site

When the preceding information is included in the design, the result permits accurate estimation of required capital investment, manufacturing costs, and potential profits. Consideration should be given to the types of buildings, heating, ventilating, lighting, power, drainage, waste disposal, safety facilities, instrumentation, etc.

Firm process designs can be prepared for purchasing and construction. Detailed drawings are made for the fabrication of special equipment, and specifications are prepared for purchasing standard types of equipment and materials. A complete plant layout is prepared, and blueprints and instructions for construction are developed. Piping diagrams and other construction details are included. Specifications are given for warehouses, laboratories, guardhouses, fencing, change houses, transportation facilities, and similar items. The final firm process design must be developed with the assistance of persons skilled in various engineering fields, such as architectural, ventilating, electrical, and civil.

Construction and Operation. When a definite decision to proceed with the construction of a plant is made, there is usually an immediate demand for a quick plant start-up. Timing, therefore, is particularly important in plant construction. Long delays may be encountered in the fabrication of major pieces of equipment, and steel deliveries often lag far behind the date of ordering. These factors must be taken into consideration when developing the final plans.

The design engineers should work in close conjunction with construction personnel during the final stages of construction and purchasing designs. In this way, the design sequence can be arranged to make certain the important factors that might delay construction are given first consideration. Construction of the plant may be started before the final design is 100 per cent complete. Correct design sequence is then essential in order to avoid construction delays.

During construction of the plant, the design engineer should visit the plant site to assist in interpretation of the plans and learn methods for improving future designs. The design engineer should also be available during the initial start-up of the plant and the early phases of operation. Thus, by close teamwork between design, construction, and operations personnel, the final plant can develop from the drawing-board stage to an operating unit that can function both efficiently and effectively.

DESIGN INFORMATION FROM THE LITERATURE

A survey of the literature will often reveal general information and specific data pertinent to the development of a design project. One good method for starting a literature survey is to obtain a recent publication dealing with the subject under investigation. This publication will give additional references, and each of these references will, in turn, indicate other sources of information. This approach permits a rapid survey of the important literature.

Chemical Abstracts, published semimonthly by the American Chemical Society, can be used for comprehensive literature surveys on chemical processes and operations.* This publication presents a brief outline and the original reference of published articles dealing with chemistry and related fields. Yearly and decennial indexes of subjects and authors permit rapid location of articles concerning specific topics.

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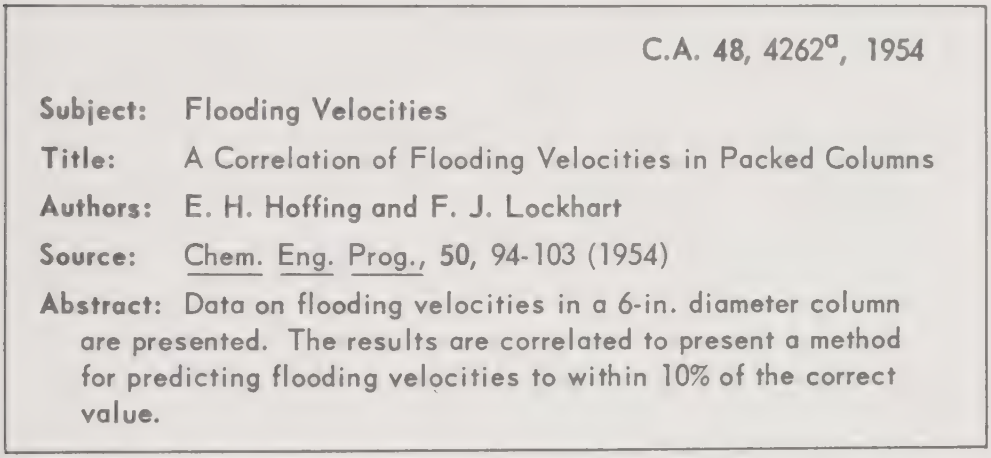
* Abstracts of general engineering articles are available in the *Engineering Index*.

Figure 10-1 shows the typical form of a card for recording information from the *Abstracts*. The notation in the upper right-hand corner indicates the *Chemical Abstracts* volume, page number and paragraph, and year. If the article appears to be of value, further information can be obtained from the original reference.



C.A. 48, 4262^a, 1954

Subject: Flooding Velocities

Title: A Correlation of Flooding Velocities in Packed Columns

Authors: E. H. Hoffing and F. J. Lockhart

Source: Chem. Eng. Prog., 50, 94-103 (1954)

Abstract: Data on flooding velocities in a 6-in. diameter column are presented. The results are correlated to present a method for predicting flooding velocities to within 10% of the correct value.

FIG. 10-1. Sample of card used for recording information from the *Chemical Abstracts*.

Annual reviews of publications in the fields of unit processes, unit operations, materials of construction, and chemical engineering fundamentals are published in *Industrial and Engineering Chemistry*. In addition to *Industrial and Engineering Chemistry*, there are many other periodicals that publish articles of direct interest to the design engineer. The following periodicals are valuable sources of information for the chemical engineer who wishes to keep abreast of the latest developments in his field: *American Institute of Chemical Engineers' Journal*, *Chemical Engineering Progress*, *Chemical Engineering*, *Chemical and Engineering News*, *Chemical Engineering Science*, *Journal of the American Chemical Society*, *Journal of Physical Chemistry*, *Petroleum Refiner*, *Engineering News-Record*, and *Transactions of the Faraday Society*.

A large number of textbooks covering the various aspects of chemical engineering principles and design are available.* In addition, many handbooks have been published giving physical properties and other basic data which are very useful to the design engineer. Examples of handbooks and other data sources of particular value to the chemical engineer are presented in the following list (name following the title is that of the editor):

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* For example, see the *Chemical Engineering Series* listing at the front of this book.

"American Electricians' Handbook," T. Croft and C. C. Carr, McGraw-Hill Book Company, Inc., New York.

"Architects' and Builders' Handbook," E. E. Kidder and H. Parker, John Wiley & Sons, Inc., New York.

"Chemical Business Handbook," J. H. Perry, McGraw-Hill Book Company, Inc., New York.

"Chemical Engineers' Handbook," J. H. Perry, McGraw-Hill Book Company, Inc., New York.

"Civil Engineering Handbook," L. C. Urquhart, McGraw-Hill Book Company, Inc., New York.

"Corrosion Handbook," H. H. Uhlig, John Wiley & Sons, Inc., New York.

"Electrical Engineers' Handbook," H. Pender, John Wiley & Sons, Inc., New York.

"Fuels and Combustion Handbook," A. J. Johnson and G. H. Auth, McGraw-Hill Book Company, Inc., New York.

"Handbook of Chemistry," N. A. Lange, Handbook Publishing Company, Sandusky, Ohio.

"Handbook of Chemistry and Physics," C. D. Hodgman, Chemical Rubber Publishing Company, Cleveland, Ohio.

"Handbook of Engineering Fundamentals," O. W. Eshbach, John Wiley & Sons, Inc., New York.

"International Critical Tables," National Academy of Sciences and National Research Council, McGraw-Hill Book Company, Inc., New York.

"Kent's Mechanical Engineers' Handbook," W. Kent, John Wiley & Sons, Inc., New York.

"Mechanical Engineers' Handbook," L. S. Marks, McGraw-Hill Book Company, Inc., New York.

"Physical Constants of the Principal Hydrocarbons," M. P. Doss, The Texas Company, New York.

"Physical Properties of Hydrocarbons," G. Egloff, A.C.S. Monograph No. 78, Reinhold Publishing Corporation, New York.

"Piping Handbook," S. Crocker, McGraw-Hill Book Company, Inc., New York.

"Plant Engineering Handbook," W. Staniar, McGraw-Hill Book Company, Inc., New York.

"Practical Design Handbook for Engineers," A. Cibulka, Highlands, Texas.

"Selected Values of Physical and Thermodynamic Properties of Hydrocarbons and Related Compounds," A.P.I., Carnegie Press, Pittsburgh, Pa.

"Standard Handbook for Electrical Engineers," A. E. Knowlton, McGraw-Hill Book Company, Inc., New York.

Trade bulletins are published regularly by most manufacturing concerns, and these bulletins give much information of direct interest to the design engineer. Some of the trade-bulletin information is condensed in an excellent reference book on chemical engineering equipment, products, and manufacturers. The book is known as the "Chemical Engineering Catalog," * and it contains a large amount of valuable descriptive material.

New information is constantly becoming available through publication in periodicals, books, trade bulletins, government reports, university bulletins, and many other sources. Many of the publications are devoted to short-cut methods for estimating physical properties or making design calculations, while others present convenient compilations of essential data in the form of nomographs or tables.

The effective design engineer must make every attempt to keep an up-to-date knowledge of the advances in his field. Personal experience and contacts, attendance at meetings of technical societies and industrial expositions, and reference to the published literature are very helpful in giving the engineer the background information necessary for a successful design.

COMPARISON OF DIFFERENT PROCESSES

In the course of a design project it is necessary to determine the most suitable process for obtaining a desired product. Several different manufacturing methods may be available for making the same material, and the various processes must be compared in order to pick the one best suited to the existing conditions.

The comparison can be accomplished through the development of complete designs. In many cases, however, all but one or two of the possible processes can be eliminated by a weighted comparison of the essential variable items, and detailed design calculations for each process may not be required. The following items should be considered in a comparison of this type:

1. Technical factors
    - *a.* Process flexibility
    - *b.* Continuous operation
    - *c.* Special controls involved
    - *d.* Commercial yields
    - *e.* Technical difficulties involved
    - *f.* Power consumption
    - *g.* Special auxiliaries required
    - *h.* Possibility of future developments
    - *i.* Health and safety hazards involved

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* Published annually by Reinhold Publishing Corporation, New York.

2. Raw materials
   - *a.* Present and future availability
   - *b.* Processing required
   - *c.* Storage requirements
   - *d.* Handling of materials
3. Waste products and by-products
   - *a.* Amount produced
   - *b.* Value
   - *c.* Potential markets and uses
   - *d.* Manner of discard
4. Equipment
   - *a.* Availability
   - *b.* Materials of construction
   - *c.* Initial costs
   - *d.* Maintenance and installation costs
   - *e.* Replacement requirements
   - *f.* Special designs
5. Plant location
   - *a.* Amount of land required
   - *b.* Transportation facilities
   - *c.* Proximity to markets and raw-material sources
   - *d.* Availability of service and power facilities
   - *e.* Availability of labor
   - *f.* Climate
   - *g.* Legal restrictions and taxes
6. Costs
   - *a.* Raw materials
   - *b.* Depreciation
   - *c.* Other fixed charges
   - *d.* Processing and overhead
   - *e.* Special labor requirements
   - *f.* Real estate
   - *g.* Patent rights

Batch versus Continuous Operation. When comparing different processes, consideration should always be given to the advantages of continuous operation over batch operation. In many cases, costs can be reduced by using continuous instead of batch processes. Less labor is required, and control of the equipment and grade of final product is simplified. Whereas batch operation was common in the early days of the modern chemical industry, more and more processes are being switched completely or partially to continuous operation. The advent of many new types of control instruments has made this transition possible, and the design engineer should be aware of the advantages inherent in any type of continuous operation.

FLOW DIAGRAMS

The design engineer uses flow diagrams to show the sequence of equipment and unit operations in the over-all process, to simplify visualization of the manufacturing procedures, and to indicate the quantities of materials and energy transfer. These diagrams may be divided into three general types: (1) qualitative, (2) quantitative, and (3) combined-detail.

A qualitative flow diagram indicates the flow of materials, unit opera-

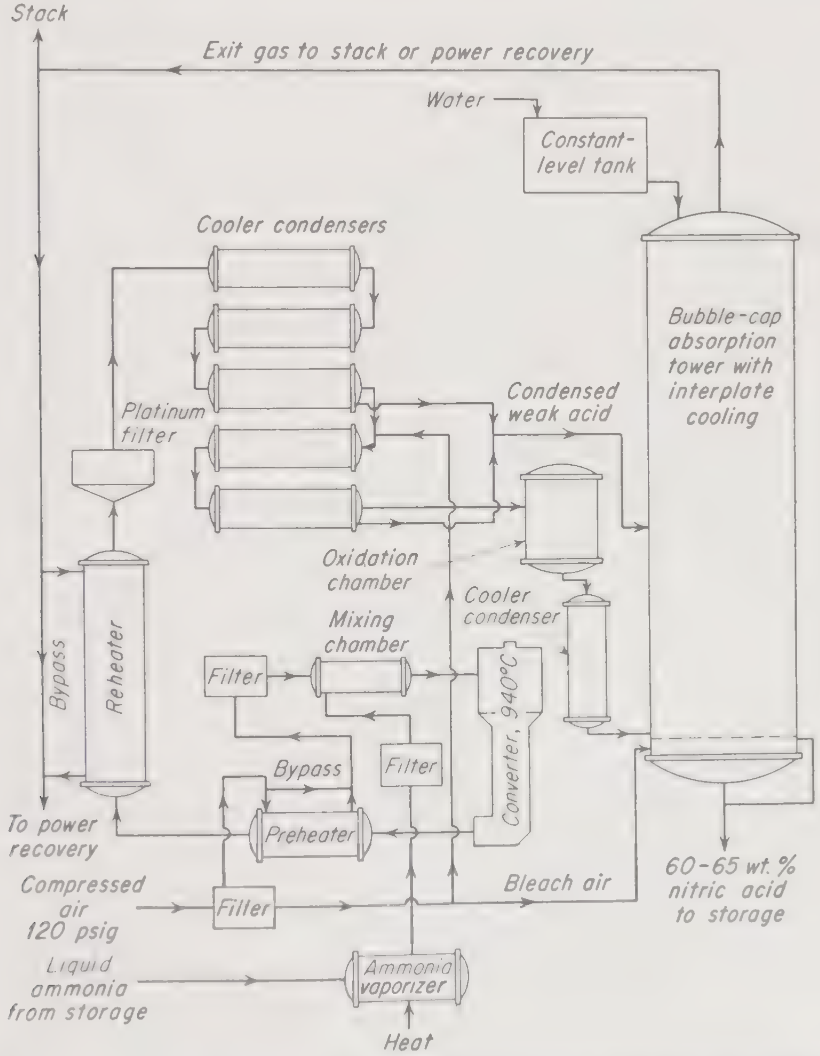

FIG. 10-2. Qualitative flow diagram for the manufacture of nitric acid by the ammonia-oxidation process.

tions involved, equipment necessary, and special information on operating temperatures and pressures. A quantitative flow diagram shows the quantities of materials required for the process operation. An example of a qualitative flow diagram for the production of nitric acid is shown in Fig. 10-2. Figure 10-3 presents a quantitative flow diagram for the same process.

Preliminary flow diagrams are made during the early stages of a design project. As the design proceeds toward completion, detailed information on flow quantities and equipment specifications become available, and combined-detail flow diagrams can be prepared. This type of diagram shows the qualitative flow pattern and serves as a base reference for giving equip-

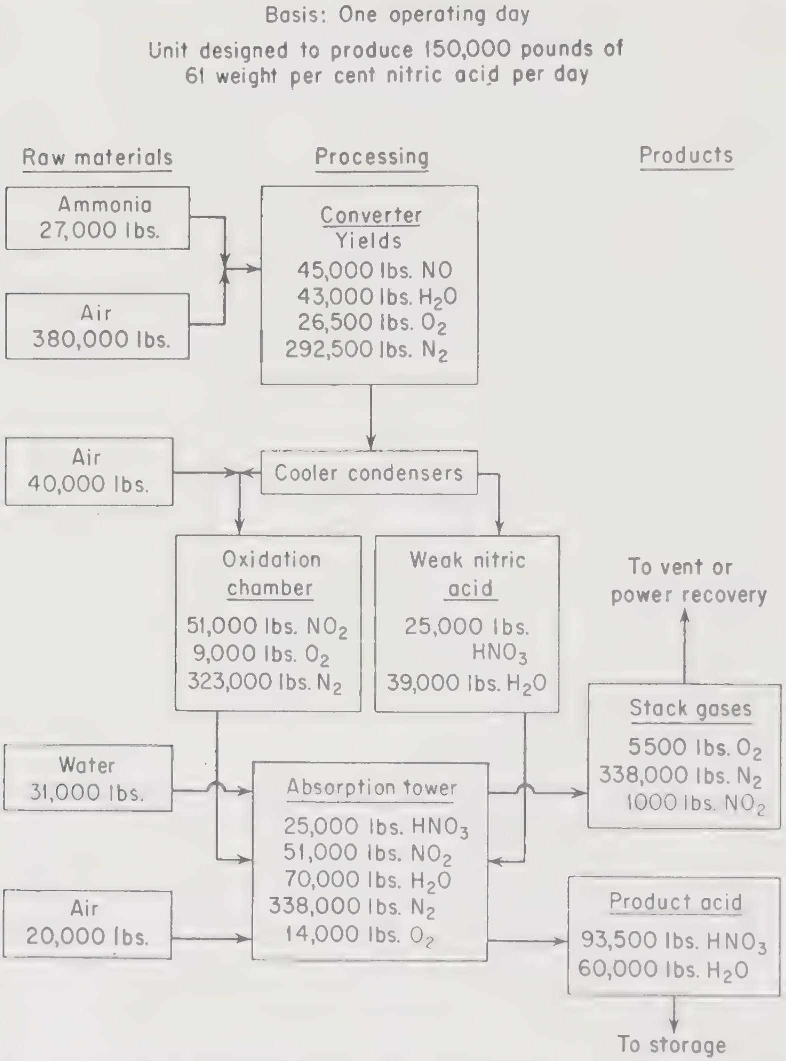

FIG. 10-3. Quantitative flow diagram for the manufacture of nitric acid by the ammonia-oxidation process.

ment specifications, quantitative data, and sample calculations. Tables presenting pertinent data on the process and the equipment are cross-referenced to the drawing. In this way, qualitative information and quantitative data are combined on the basis of one flow diagram. The drawing does not lose its effectiveness by presenting too much information; yet the necessary data are readily available by direct reference to the accompanying tables.

A typical combined-detail flow diagram shows the location of temperature and pressure regulators and indicators, as well as the location of critical control valves and special instruments. Each piece of equipment is shown and is designated by a defined code number. For each piece of equipment, accompanying tables give essential information, such as specifications for purchasing, specifications for construction, type of fabrication, quantities and types of chemical involved, and sample calculations.

PLANT LOCATION

The geographical location of the final plant can have a strong influence on the success of an industrial venture. Much care must be exercised in choosing the plant site, and many different factors must be considered. Primarily, the plant should be located where the minimum cost of production and distribution can be obtained, but other factors, such as room for expansion and general living conditions, are also important.

An approximate idea as to the plant location should be obtained before a design project reaches the detailed-estimate stage, and a firm location should be established upon completion of the detailed-estimate design. The choice of the final site should first be based on a complete survey of the advantages and disadvantages of various geographical areas and, ultimately, on the advantages and disadvantages of available real estate.

The following factors should be considered in choosing a plant site:

1. Raw materials
2. Markets
3. Power and fuel
4. Climate
5. Transportation facilities
6. Water supply
7. Waste disposal
8. Labor supply
9. Taxation and legal restrictions
10. Room for expansion
11. Flood and fire protection
12. Site characteristics
13. Proximity to industrial centers

Raw Materials. The source of raw materials is one of the most important factors influencing the selection of a plant site. This is particularly true if large volumes of raw materials are consumed, because location near the raw-materials source permits considerable reduction in transportation and storage charges. Attention should be given to the purchased price of the raw materials, distance from the source of supply, freight or transportation expenses, reliability of supply, purity of the available raw materials, and storage requirements.

Markets. The location of markets or intermediate distribution centers affects the cost of product distribution and the time required for shipping. Proximity to the major markets is an important consideration in the selection of a plant site, because the buyer usually finds it advantageous to purchase from nearby sources. It should be noted that markets are needed for by-products as well as for the major final products.

Power and Fuel. Power and steam requirements are high in most industrial plants, and fuel is ordinarily required to supply these utilities. Consequently, power and fuel can be combined as one major factor in the choice of a plant site. Electrolytic processes require a cheap source of electricity, and plants using electrolytic processes are often located near large hydroelectric installations. If the plant requires large quantities of coal or oil, location near a source of fuel supply may be essential for economic operation. The local cost of power can help determine whether power should be purchased or self-generated.

Climate. If the plant is located in a cold climate, costs may be increased by the necessity for construction of protective shelters around the process equipment, and special cooling towers or air-conditioning equipment may be required if the prevailing temperatures are high. Excessive humidity or extremes of hot or cold weather can have a serious effect on the economic operation of a plant, and these factors should be examined when picking a plant site.

Transportation Facilities. Water, railroads, and highways are the common means of transportation used by industrial concerns. The kind and amount of products and raw materials determine the most suitable type of transportation facilities. In any case, careful attention should be given to local freight rates and existing railroad lines. The proximity to railroad centers and the possibility of canal, river, lake, or ocean transport must be considered. Motor trucking facilities are widely used and can serve as a useful supplement to rail and water facilities. If possible, the plant site should have access to all three types of transportation, and, certainly, at least two types should be available. There is usually need for convenient air and rail transportation between the plant and the main company headquarters, and effective transportation facilities for the plant workers are necessary.

Water Supply. The process industries use large quantities of water for cooling, washing, steam generation, and as a raw material. The plant, therefore, must be located where a dependable supply of water is available. A large river or lake is preferable, although deep wells or artesian wells may be satisfactory if the amount of water required is not too great. The level of the existing water table can be checked by consulting the state geological survey, and information on the constancy of the water table and the year-round capacity of local rivers or lakes should be obtained. If the water supply shows seasonal fluctuations, it may be desirable to construct a reservoir or to drill several stand-by wells. The temperature, mineral content, silt or sand content, bacteriological content, and cost for supply and purification treatment must also be considered when choosing a water supply.

Waste Disposal. In recent years, many legal restrictions have been placed on the methods for disposing of waste materials from the process industries. The site selected for a plant should have adequate capacity and facilities for correct waste disposal. Even though a given area has no restrictions on pollution, it should not be assumed that this condition will continue to exist. Waste disposal can be accomplished by water, land, or air dispersal. In choosing a plant site, the permissible tolerance levels for the various methods of waste disposal should be considered, and attention should be given to potential requirements for additional waste-treatment facilities.

Labor Supply. The type and supply of labor available in the vicinity of a proposed plant site must be examined. Consideration should be given to prevailing pay rates, restrictions on number of hours worked per week, competing industries that can cause dissatisfaction or high turnover rates among the workers, racial segregation, and variations in the skill and intelligence of the workers.

Taxation and Legal Restrictions. State and local tax rates on property, income, unemployment insurance, and similar items vary from one location to another. Similarly, local regulations on zoning, building codes, nuisance aspects, and transportation facilities have an influence on the final choice of a plant site.

Room for Expansion. Future changes may make it desirable or necessary to expand the plant facilities. Therefore, even though no immediate expansion is planned, a new plant should be constructed at a location where additional space is available.

Flood and Fire Protection. Many industrial plants are located along rivers or near large bodies of water, and there are risks of flood or hurricane damage. Before choosing a plant site, the regional history of natural events of this type should be examined and the consequences of such occurrences considered. Protection from losses by fire is another important factor in picking a plant location. In case of a major fire, assistance from outside fire departments should be available. Fire hazards in the immediate area surrounding the plant site must not be overlooked.

Site Characteristics. The characteristics of the land at a proposed plant site should be examined carefully. The topography of the tract of land and the soil structure must be considered, since they may have a pronounced effect on construction costs. The cost of the land is important, as well as local building costs and living conditions.

Proximity to Industrial Centers. Location near large industrial centers has the advantage of giving a large supply of labor and a wide variety of transportation facilities. Proximity to other industrial concerns may permit reduced prices on certain necessary materials and services. On the other hand, there are many advantages to location in rural areas. Real estate is usually cheaper, and there is less tendency for excessive labor turnover. Taxes may be much lower, and there are fewer restrictive ordinances. In case of a major disaster, such as a nuclear-bomb attack or an explosion, location in an isolated area would be very beneficial.

Selection of the Plant Site. The major factors in the selection of most plant sites are (1) raw materials, (2) markets, (3) power and fuel, (4) climate, (5) transportation facilities, and (6) water supply. For a preliminary survey, the first four of these should be considered. Thus, on the basis of raw materials, markets, power and fuel, and climate, acceptable locations can usually be reduced to one or two general geographical regions. For example, the preliminary survey might indicate that the best location for a particular plant would be in the south central or southeastern part of the United States.

In the next step, the effects of transportation facilities and water supply are taken into account. This permits reduction of the possible plant location to several general target areas. These areas can then be reduced further by considering all the factors that have an influence on plant location.

As a final step, a detailed analysis of the remaining sites can be made. Exact data on items such as freight rates, labor conditions, tax rates, price of land, and general local conditions can be obtained. The various sites can be inspected and appraised on the basis of all the factors influencing the final decision. Many times, the advantages of locating a new plant on land or near other facilities already owned by the concern that is building the new plant outweigh the disadvantages of the particular location. In any case, however, the final decision on choosing the plant site should take into consideration all the factors that can affect the ultimate success of the over-all operation.

PLANT LAYOUT

The physical layout of a plant should permit coordination between the operation of process equipment and the use of storage and materials-handling facilities. A detailed plan of the plant layout should be developed in conjunction with a firm process design. The layout can play an important part in determining construction and manufacturing costs, and it must be planned carefully with attention being given to future problems that may arise. The following factors should be considered: *†

1. Type and quantity of product to be manufactured
2. Possible changes in the future
3. Storage facilities readily available for use
4. Process operation arranged for operators' convenience
5. Space available and space required
6. Time interval between successive operations
7. Automatic or semiautomatic controls
8. Safety consideration
9. Availability of utilities and services
10. Waste disposal
11. Necessary control tests
12. Auxiliary equipment
13. Gravity flow
14. Type of buildings
15. Problems in plant construction
16. Accessibility of equipment and piping for repairs, maintenance, and inspection

Preparation of the Layout. Scale drawings, complete with elevation indications, can be used for determining the best location for equipment and facilities. Elementary layouts are developed first. These show the fundamental relationships between storage space and operating equipment. The next step requires consideration of the operational sequence and gives a primary layout based on flow of materials, unit operations, storage, and future expansion. Finally, by analyzing all the factors that are involved in plant layout, a detailed recommendation can be presented, and drawings and elevations, including isometric drawings of the piping systems, can be prepared.

Templates, or small cutouts constructed to a selected scale, are useful for making rapid and accurate layouts, and three-dimensional models are often made. The use of such models for making certain a proposed plant layout is correct has found increasing favor in recent years. A scale of ¼ in. = 1 ft is commonly employed.

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* J. M. Apple, "Plant Layout and Materials Handling," The Ronald Press Company, New York, 1950.

† R. W. Mallick and A. A. Gaudreau, "Plant Layout—Planning and Practice," John Wiley & Sons, Inc., New York, 1951.

Figure 10-4 shows a view of a typical model for an industrial plant. Errors in a plant layout are easily located when three-dimensional models are used, since the operations and construction engineers can immediately see errors which might have escaped notice on two-dimensional templates or blueprints. In addition to increasing the efficiency of a plant layout, models are very useful during plant construction and for instruction and orientation purposes after the plant is completed.

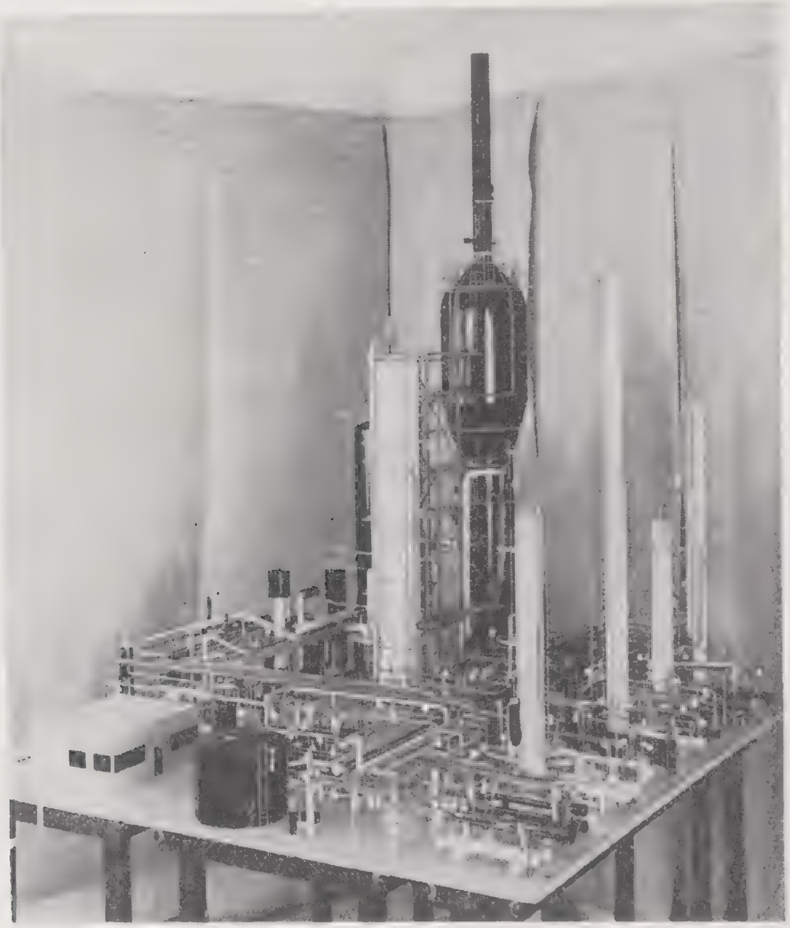

FIG. 10-4. Scale model showing details of plant layout. (*M. W. Kellogg Company.*)

PLANT OPERATION AND CONTROL

In the design of an industrial plant, the methods which will be used for plant operation and control help determine many of the design variables. For example, the extent of instrumentation can be a factor in choosing the type of process and setting the labor requirements. Health and safety hazards involved in the operation must not be overlooked, and it should be remembered that maintenance work will be necessary to keep the installed equipment and facilities in good operating condition. The design engineer must recognize the importance of factors of this type which are directly related to plant operation and control, and he must take them into proper account during the development of a design project.

Instrumentation

Instruments are used in the chemical industry to measure process variables, such as temperature, pressure, density, viscosity, specific heat, conductivity, pH, humidity, dew point, liquid level, flow rate, chemical composition, and moisture content. By use of instruments having varying degrees of complexity, the values of these variables can be recorded continuously and controlled within narrow limits.

Automatic control has been accepted generally throughout the chemical industry, and the resultant savings in labor combined with improved ease and efficiency of operation has more than offset the added expense for in-

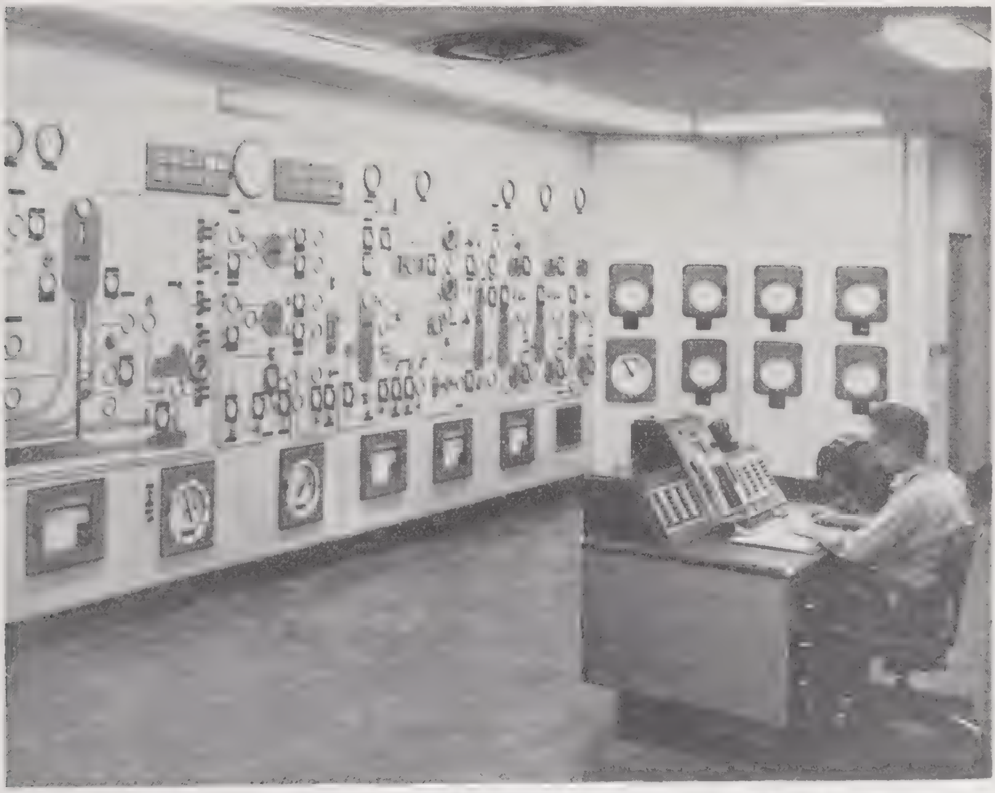

Fig. 10.5. Example of a graphic panel for a fluid catalytic cracking unit. (*C. F. Braun and Company.*)

strumentation. Effective utilization of the many instruments employed in a chemical process is achieved through centralized control, whereby one centrally located control room is used for the indication, recording, and regulation of the process variables. Panel boards have been developed which present a graphical representation of the process and have the instrument controls and indicators mounted at the appropriate locations in the over-all process. This helps a new operator to familiarize himself quickly with the significance of the instrument readings, and rapid location of any operational variance is possible. An example of a graphic panel in a modern industrial plant is shown in Fig. 10-5.

Because of the many variables found in processing and the wide range over which these variables must be determined and controlled, the assistance of a skilled instrumentation engineer is essential in setting up a control system. Instrumentation problems caused by transmission lags, cycling due to slow or uncompensated response, radiation errors, or similar factors are commonly encountered in plant operation, but most of these problems can be eliminated if the control system is correctly designed.

Maintenance

Many of the problems involved in maintenance are caused by the original design and layout of plant and equipment. Sufficient space for maintenance work on equipment and facilities must be provided in the plant layout, and the engineer should consider maintenance requirements when he is making his decisions on equipment.

Too often, the design engineer is conscious only of first costs and fails to recognize that maintenance costs can easily nullify the advantages of a cheap initial installation. For example, a close-coupled motor pump utilizing a high-speed motor may require less space and lower initial cost than a standard motor combined with a coupled pump. However, if replacement of the impeller and shaft becomes necessary, the repair cost with a close-coupled motor pump is much greater than with a regular coupled pump. The use of a high-speed motor reduces the life of the impeller and shaft, particularly if corrosive liquids are involved. If the design engineer fails to consider the excessive maintenance costs that may result, he can make the error of recommending the cheaper and smaller unit. Similarly, a compact system of piping, valves, and equipment may be cheap and convenient for the operators' use, but maintenance of the system may require costly and time-consuming dismantling operations.

Health and Safety

Toxic and corrosive chemicals, fires, explosions, falls, and mechanical equipment are the major health and safety hazards encountered in the operation of plants in the process industries. The design engineer must be aware of these hazards, and he must make every attempt to present a design which provides the maximum protection for the plant personnel and the minimum chance for the occurrence of accidents.

Chemical Hazards. Many chemicals can cause dangerous burns if they come in contact with living tissue. Dehydration by strong dehydrating agents, digestion by strong acids and bases, and oxidation by strong oxidizing agents can destroy living tissue. Eyes and the mucous membranes of the nose and throat are particularly susceptible to the effects of corrosive dusts, mists, and gases. In addition to having the ability to destroy living tissue, many chemicals are very poisonous or are prone to burn or explode. Tolerance levels for toxic chemicals are presented in Table 1, and Table 2 shows the explosive limits for various flammable materials.

Fire and Explosion Hazards. The chances that a single fire or explosion will spread to adjoining units can be reduced by careful plant layout and judicious choice of constructional materials. Hazardous operations should be isolated by location in separate buildings or by the use of brick fire walls. Brick or reinforced concrete walls can serve to limit the effects of an explosion, particularly if the roof is designed to lift easily under an explosive force.

Equipment should be designed to meet the specifications and codes of recognized authorities, such as the American Standards Association, American Petroleum Institute, American Society for Testing Materials, Factory Mutual Laboratories, National Fire Protection Association, and Underwriters' Laboratories. The design and construction of pressure vessels and storage tanks should follow API and ASME Codes, and the vessels should be tested at 1.5 to 2 or more times the design pressure. Adequate venting is necessary, and it is advisable to provide protection by using both spring-loaded valves and rupture disks.

Possible sources of fire are reduced by eliminating all unnecessary ignition sources, such as flames, sparks, or heated materials. Matches, smoking, welding and cutting, static electricity, spontaneous combustion, and non-explosion-proof electrical equipment are all potential ignition sources.

The installation of sufficient fire alarms, temperature alarms, fire-fighting equipment, and sprinkler systems must be specified by the design engineer. First-aid stations, protected walkways and work areas, and effective guards on moving parts of equipment should be provided in the final plant, and every attempt should be made to incorporate facilities for health and safety protection in the original design.

TABLE 1. TOLERANCE LEVELS FOR TOXIC GASES AND VAPORS *†

Substance	Maximum safe atmospheric concentration for 8-hr exposure, ppm	Usual mode of entrance to body	Signs and symptoms of poisoning
Acetone	500	Inhalation	Irritation of skin, eyes, and upper respiratory tract
Ammonia	100	Inhalation	Severe irritation of eyes and respiratory passage, cough, caustic action on skin
Aniline	5	Absorption through skin, inhalation, or ingestion	*Acute:* weakness, dizziness, blueness of lips, fainting *Chronic:* disturbances of equilibrium, nausea, vomiting, diarrhea, eczema, sleepiness and irritability
Benzene	50	Inhalation	*Acute:* inebriation, convulsions and loss of consciousness *Chronic:* weakness, fatigue, bleeding from the gums and nose, headache, dizziness
Butanol	50	Inhalation	No known industrial poisonings, local anesthetic, narcotic, produces dermatitis
Carbon disulfide	20	Inhalation, absorption through skin	*Acute:* headache, dizziness, breathlessness, abdominal pain, loss of consciousness followed or preceded by delirium *Chronic:* fatigue, dizziness, pain in the arms and legs, headache, general nervousness, failure of vision, nausea, vomiting, pain in the stomach, constipation
Carbon monoxide	100	Inhalation	*Acute:* dizziness, headache, nausea, redness of skin, coma, difficult breathing *Subacute:* insomnia and failure of memory in addition to general symptoms of acute poisoning
Carbon tetrachloride	50	Inhalation	*Acute:* headache, nausea, vomiting, dulling of senses, loss of consciousness *Chronic:* nausea, loss of appetite, loss of weight, dizziness, mental dullness
Chlorine	2	Inhalation	*Acute:* irritation of the eyes, nose, and throat; choking; serious delayed lung effects *Chronic:* cough, nasal and bronchial catarrh, eroded teeth
Chlorobenzene	75	Inhalation	*Acute:* sleepiness, loss of consciousness, twitching or tremors of extremities *Chronic:* headache, dizziness
Ethyl ether	400	Inhalation	*Acute:* unconsciousness, paralysis, headache, loss of appetite
Ethylene dichloride	75	Inhalation	*Acute:* irritation of eyes and nose, dizziness, loss of coordination, nausea, vomiting
Formaldehyde	10	Inhalation, direct action on skin	*Acute:* irritation of eyes, nose, and throat; sensitization of skin

TABLE 1. TOLERANCE LEVELS FOR TOXIC GASES AND VAPORS (*Continued*)

Substance	Maximum safe atmospheric concentration for 8-hr exposure, ppm	Usual mode of entrance to body	Signs and symptoms of poisoning
Gasoline	500	Inhalation	*Acute:* "naphtha jag," headache, dizziness, nausea, vomiting, sleepiness
Hydrogen chloride	10	Inhalation	*Acute:* irritation and burns of any tissue exposed to it, violent coughing and difficult breathing
Hydrogen cyanide	20	Inhalation, skin absorption	*Acute:* constriction in throat, nausea, dizziness, headache, cold sweat, sometimes convulsions
Hydrogen fluoride	3	Inhalation	*Acute:* direct and serious irritation and burns of skin and mucous membranes
Hydrogen sulfide	20	Inhalation	*Acute:* asphyxiation *Subacute:* pain and burning sensation in eyes, nose, and throat; headaches; sleepiness; dizziness; fatigue
Mercury and its compounds	0.10 mg/cu m	Inhalation as dust or vapor, absorption through skin	*Chronic:* increased flow of saliva, swelling and inflammation of gums, irritability, tremors
Methyl alcohol	200	Inhalation	*Acute:* dizziness, stupor, cramps, digestive disturbances, dilated pupils, blue lips
Nitrogen oxides and nitric acid	25	Inhalation	*Acute:* severe corrosive action on skin and mucous membranes, cough, difficult breathing, delayed lung irritation
Nitroglycerine	0.5	Inhalation, skin absorption	*Acute:* flushed face, throbbing headache, dizziness, tremors, mental disturbances, fainting, nausea, vomiting
Phosgene	1	Inhalation	*Acute:* irritation of eyes, coughing, feeling of pressure in chest, severe lung effects delayed for some hours after exposure
Sulfur dioxide	10	Inhalation	*Acute:* irritation of eyes, nose, and throat; coughing; and choking
Toluene	200	Inhalation	Similar to benzene but somewhat less toxic
Xylene	200	Inhalation	Similar to benzene but considerably less toxic

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* F. A. Patty, "Industrial Hygiene and Toxicology," Interscience Publishers, Inc., New York, vol. I, 1948, vol. II, 1949.

† "Accident Prevention Manual for Industrial Operations," 2d ed., National Safety Council, Inc., Chicago, 1951.

TABLE 2. EXPLOSIVE LIMITS FOR FLAMMABLE MATERIALS *

Flash point = lowest temperature at which a liquid gives off enough vapor to form flammable mixtures with air which are capable of propagating flame when ignited. Auto ignition temperature = lowest temperature at which a flammable gas- or vapor-air mixture will ignite solely by heat.

Substance	Flash point, °F	Auto ignition temperature, °F	Explosive or flammable limits, % by volume in air	
			Lower	Upper
Acetaldehyde	−17	365	4.0	57
Acetone	0	1000	2.55	12.8
Acetylene	Gas	635	2.5	80
Ammonia	Gas	1204	16	25
Aniline	168	1000		
Benzene	12	1000	1.5	8
n-Butane	−76	806	1.6	8.5
n-Butanol	100	650	1.7	
Carbon disulfide	−22	212	1.0	50
Carbon monoxide	Gas	1204	12.5	74
Ethane	Gas	950	3.2	12.5
Ethyl acetate	24	800	2.18	11.5
Ethyl alcohol	55	700	3.5	19
Ethyl chloride	−58	966	3.7	12.0
Ethyl ether	−49	356	1.85	36.5
Ethylene	Gas	842	2.75	28.6
Ethylene dichloride	56	775	6.2	15.9
Ethylene glycol	232	775	3.2	
Formaldehyde	130	806		
Gasoline	−50	495	1.3	6
Heptane	−4	451	1.0	6
Hexane	−15	500	1.2	6.9
Hydrogen	Gas	1085	4.1	74.2
Hydrogen sulfide	Gas	500	4.3	46
Isopropyl alcohol	53	750	2.5	
Methane	Gas	999	5.3	14.0
Methyl alcohol	52	800	6	36.5
Methyl chloride	Gas	1170	8.2	19.7
Methylcyclohexane	25	545	1.15	
Pentane	<−40	588	1.45	7.5
Propane	Gas	871	2.37	9.5
Toluene	40	1026	1.27	7.0
Turpentine	95	464	0.8	
Xylene	63	900	1	5.3

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* "Accident Prevention Manual for Industrial Operations," 2d ed., National Safety Council, Inc., Chicago, 1951.

POWER SUPPLY AND TRANSMISSION

The primary sources of raw energy for the supply of power are found in the heat of combustion of fuels and in elevated water supplies. Fuel-burning plants are of greater industrial significance than hydroelectric installations because the physical location of fuel-burning plants is not restricted. At the present time, the most common fuels are coal, oil, and gas. However, a rapidly developing source of power is nuclear energy, which may ultimately replace many of our present power-producing installations.

In the chemical industries, power is supplied primarily in the form of electrical energy. Agitators, pumps, hoists, blowers, compressors, and similar equipment are usually operated by electric motors, although other prime movers, such as steam engines, internal-combustion engines, and hydraulic turbines are sometimes employed.

When a design engineer is setting up the specifications for a new plant, he must decide whether to use purchased power or have the plant set up its own power unit. It may be possible to obtain steam for processing and heating as a by-product from the self-generation of electricity, and this factor may influence the final decision. In any case, power should be available to the plant from at least two independent sources to permit continued operation of the plant facilities if one of the power sources fails.

Power can be transmitted in various forms, such as mechanical energy, electrical energy, heat energy, and pressure energy. The design engineer should recognize the different methods for transmitting power, and he must choose the ones best suited to his particular process.

The transmission of mechanical power must be accomplished in all types of industrial processes. Some examples of standard items used industrially for the transmission of mechanical power are belts, pulleys, shafts, chain drives, ropes, couplings, gear reducers, clutches, and bearings.*

Electrical Power Transmission

Although the details of electrical power transmission should be handled by an experienced electrical engineer, the chemical engineer needs to specify many of the requirements for the electrical power system. In particular, the chemical engineer in design work should be acquainted with electrical wiring practices and the types and characteristics of electric motors.

Wiring. All wiring installations should comply with the National Electrical Code and the National Electrical Safety Code. Conduit wiring, in which the wires are passed through metal ducts, is required for most industrial installations, although open wiring is permitted in some cases when no hazardous operations or materials are involved.

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* See W. Staniar, "Plant Engineering Handbook," McGraw-Hill Book Company, Inc., New York, 1950.

The minimum size of wire for a particular installation is determined by the *allowable current-carrying capacity* as stipulated in the Electrical Code and the *regulation* (i.e., the voltage drop over the length of the wire expressed as per cent of the full-load voltage). Reasonable regulation values can vary from 3 per cent for lighting to as high as 10 per cent for motors. Table 3 shows allowable current-carrying capacities for various wire sizes.

If conduiting is not used, the National Safety Code has additional restrictions on wire sizes to make certain the wiring system will have sufficient span strength. The final decision on size of wire and the layout of a wiring system requires consideration of the National Codes, cost of the installed wire, cost of energy loss in the wire, possible future changes in the load, and other factors related to the purpose of the wiring system.

Table 3. Allowable Current-carrying Capacity of Insulated Copper Wire
National Electrical Code

Wire size, American (or B. & S.) gauge no.	Area, cir mils	Diameter, in.	Weight, bare, lb/1000 ft	Resistance, ohms/1000 ft at 20°C	Allowable current-carrying capacity,* amp	
					Rubber insulation	Varnished-cambric insulation
18	1,624	0.040	4.9	6.38	5	
16	2,583	0.051	7.8	4.02	6	
14	4,107	0.064	12.4	2.52	15	25
12	6,530	0.081	19.8	1.59	20	30
10	10,380	0.102	31.4	0.999	30	40
8	16,510	0.128	50.0	0.628	40	50
6	26,250	0.162	79.5	0.395	55	70
4	41,740	0.204	126	0.248	70	90
2	66,370	0.258	201	0.156	95	120
1	83,690	0.289	253	0.124	110	140
0	105,500	0.325	320	0.0983	125	155
00	133,100	0.365	403	0.0779	145	185
000	167,800	0.410	508	0.0618	165	210
0000	211,600	0.460	641	0.0490	195	235
	500,000	0.815	1520	0.0216	320	405
	1,000,000	1.152	3030	0.0108	455	585

* Allowable current-carrying capacity applies for no more than three conductors in one raceway and room temperatures less than 30°C. Greater current is allowed for other insulations and for conductors in open air. Values for wire sizes larger than 0000 are for stranded wire.

Direct-current Motors. The choice of an electric motor depends on the type of current available and on the service required. The motor service determines the special mechanical features that are necessary, such as a construction which makes the motor explosion-proof, submergible, acid-proof, or moisture-proof. Cost, type and extent of control wanted, operating personnel available, and speed range needed are other factors of importance in choosing an electric motor.

Direct current is preferable to alternating current in many cases because of the convenience in adjusting speeds. *Shunt-wound motors* are commonly used when direct current is available. This type of motor can furnish nearly constant speed from no load to full load, and the speed can be adjusted by the use of field rheostats or other controls.

Series and compound-wound motors are used with direct current. *Series motors* are employed when heavy starting torques are required and when variable speed is permissible, as long as the high speeds at light loads do not exceed the safety limit. The characteristics of the shunt and series motors are combined in the *compound-wound motor*. This type of motor will handle a fairly heavy starting torque, and it has the desirable characteristic of a safe no-load speed. It is particularly useful when there are sudden requirements to handle a heavy load for a short time, as in the operation of a drill press. Although compound-wound motors can be adapted for adjustable-speed applications, they are generally not recommended for this purpose.

Alternating-current Motors. The two primary classifications of alternating-current motors are *polyphase* and *single-phase*. Further classification can be made on the basis of motor type, such as series, split-phase induction, and repulsion-induction for single-phase motors and induction, synchronous, and brush-shifting for polyphase motors.

Single-phase motors are ordinarily used only in small sizes ranging from $\frac{1}{4}$ to 10 hp. They are found in many laboratory and pilot-plant installations, but they have little utility in commercial plants where polyphase power is available and large motors are required.

Polyphase induction motors of the *squirrel-cage type* are used extensively in the process industries. There are three basic kinds of squirrel-cage induction motors as indicated in the following:

1. Low-resistance general-purpose rotor. This type of motor is not acceptable when heavy starting torques are required. It has the highest efficiency and power factor and the smallest slip of the squirrel-cage motors and is, therefore, generally used when the starting torque is adequate. The speed remains essentially constant from no load to full load.

2. High-resistance rotor. This is a special-service motor with high slip. It is used when there are periodic heavy loads of short duration or when

the service consists essentially of starting and stopping. Because of the high slip, the operating speed varies from no load to full load.

3. High-reactance rotor and double squirrel-cage rotor. These motors are used when a high starting torque is required. The double squirrel-cage type is particularly useful because of its ruggedness and starting characteristics.

Polyphase *synchronous motors* operate at constant speed from no load to full load, and they can be adjusted to give various power factors. In sizes up to about 300 hp, induction motors are less expensive than synchronous motors. When a large-size motor is selected for constant-speed operation, the synchronous motor must be given careful consideration if the power factor is of importance and if the starting-torque requirements are not too severe.

If speed adjustment is required, *wound-rotor induction motors* or *polyphase brush-shifting motors* can be used. *Multispeed motors* of the squirrel-cage induction type can be operated at different speeds by varying the number of poles.

STRUCTURAL DESIGN

One of the most important aspects in structural design for the process industries is correct foundation design with allowances for the heavy equipment and vibrating machinery used. The purpose of the foundation is to distribute the load so that excessive or damaging settling will not occur. The type of foundation depends on the load involved and the material on which the foundation acts. It is necessary, therefore, to know the characteristics of the soil at a given plant site before the structural design can be started.

The allowable bearing pressure varies for different types of soils, and the soil should be checked at the surface and at various depths to determine the bearing characteristics. The allowable bearing pressure for rock is 30 or more tons/sq ft, while that for soft clay may be as low as 1 ton/sq ft. Intermediate values of 4 to 10 tons/sq ft apply for mixtures of gravel with sand, hard clay, and hardpan.*

A foundation may simply be a wall founded on rock or hardpan, or it may be necessary to increase the bearing area by the addition of a footing. Plain concrete is usually employed for making footings, while reinforced concrete, containing steel rods or bars, is commonly used for foundation walls. If possible, a foundation should extend below the frost line, and it should always be designed to handle the maximum load.

Maintenance difficulties encountered with floors and roofs should be given particular attention in a structural design. Concrete floors are used extensively in the process industries, and special cements and coatings are available which make the floors resistant to heat or chemical attack. Flat roofs are often specified for industrial structures. Felt saturated with coal-tar pitch combined with a coal-tar pitch gravel finish is satisfactory for roofs of this type. Asphalt-saturated felt may be used if the roof has a slope of more than ½ in./ft.

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* W. Kent and C. Carmichael, "Kent's Mechanical Engineers' Handbook," 12th ed., John Wiley & Sons, Inc., New York, 1953.

Corrosive effects of the process, cost of construction, and climatic effects must be considered when choosing structural materials. Steel and concrete are the materials of construction most commonly used, although wood, aluminum, glass blocks, cinder blocks, glazed tile, bricks, and other materials are also of importance. Allowances must be made for the type of lighting and drainage, and sufficient structural strength must be provided to resist normal loads as well as extreme loads due to high winds or other natural causes.

In any type of structural design for the process industries, the function of the structure is more important than the form. The style of architecture should be subordinated to the need for supplying a structure which is adapted to the proposed process and has sufficient flexibility to permit changes in the future. Although cost is certainly important, the design engineer should never forget the fact that the quality of a structure remains apparent long after the initial cost is forgotten.

PATENTS

A patent is essentially a contract between an inventor and the public. In consideration of full disclosure of the invention to the public, the patentee is given exclusive rights to control the use and practice of the invention.* A patent gives the holder the power to prevent others from using or practicing the invention for a period of 17 years from the date of granting. In contrast, trade secrets and certain types of confidential disclosures can receive protection under common-law rights only as long as the secret information is not public knowledge.

A new design should be examined to make certain no patent infringements are involved. If the investigation can uncover even one legally expired patent covering the details of the proposed process, the method can be used with no fear of patent difficulties. Although most large corporations have patent attorneys to handle investigations of this type, the design engineer can be of considerable assistance in determining if infringements are involved. A design engineer, therefore, should have a working knowledge of the basic practices and principles of patent law.*†

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* Patents are available to the general public and can be purchased from the Commissioner of Patents, Washington 25, D.C., for a fee of $0.25 per patent. Microcard reproductions of patents are available in many libraries.

Patentable Inventions. A patent may be obtained on any new and useful process, machine, method of manufacture, composition of matter, or plant, provided it has not been known or used by others before the person applying for the patent made his invention or discovery. The invention must not have been described in a printed publication or been in public use or on sale for more than 1 year prior to the patent application. A patentable item must result from the use of creative ability above and beyond that which would be expected in the regular work of a person skilled in the particular field. Thus, a patentable item cannot be something requiring merely mechanical skill, and a patent will not be granted for a change in a previously known item or process unless the change involves something entirely new.

Patent Applications. A patent application consists of (1) a petition, directed to the Commissioner of Patents and requesting the grant of a patent, (2) an oath, sworn to before a notary public or other designated officer, (3) specifications and claims, in which the claims to be patented are indicated along with detailed specifications including drawings and other pertinent information, and (4) the filing fee. When the application is filed, the patent office gives it a serial number and informs the applicant of the number and date of filing. The application is then examined, and, after a period of time, the official action on the claim is sent to the applicant or his attorney. If the official action requires a reply, the applicant must respond within 6 months or the application is considered to be abandoned.

In giving the specifications and claims, every effort must be made to present a full disclosure. A patent can be declared invalid if it is shown that the patentee purposely held back some essential part of the invention.

A patent application must be signed by the person or persons who made the invention. It is seldom advisable, however, for the inventor to handle his own application without the assistance of an experienced patent attorney. There are so many legal phases and complex proceedings involved in obtaining full patent coverage that competent counsel is practically a necessity.

Foreign Patents. A United States patent is enforceable only in the United States and its territories. Similarly, patents granted in a foreign country apply only to that particular country. A patent must be obtained in each foreign country where protection of the invention is desired.

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* Statutes and general rules applying to United States patents are presented in the two pamphlets "Patent Laws" and "Rules of Practice of the United States Patent Office in Patent Cases," U.S. Government Printing Office.

† References of particular interest to chemical engineers are C. H. Biesterfeld, "Patent Law for Lawyers, Students, Chemists, and Engineers," 2d ed., John Wiley & Sons, Inc., New York, 1949; J. K. Wise, "Patent Law in the Research Laboratory," Reinhold Publishing Corporation, New York, 1955.

Under the regulations set up by the International Convention for the Protection of Industrial Property, an inventor can obtain the benefit of a previous foreign filing date provided the application is filed in this country within 12 months of the foreign filing date. A statutory requirement for the granting of a patent is that it cannot have been patented by the inventor or his legal representatives in a foreign country on an application filed more than 12 months before being filed in this country.

Interferences. The situation often arises in which two or more independent patent applications covering essentially the same invention are on file in the U.S. Patent Office. When this occurs, a proceeding called an *interference* is instituted to determine who is entitled to the patent. An interference may also be instituted between a pending application and a granted patent. It is obvious that patents on identical inventions cannot be granted to separate parties, even though each may be an original inventor. Interferences are decided on the basis of priority. The patent is granted to the applicant who was first to conceive the idea for the invention, providing he exercised reasonable diligence in reducing it to practice.

Because of the role of priority in any type of interference proceeding, it is very important for an inventor to maintain complete records. A written description and sketches should be prepared by an inventor as soon as possible after the conception of an idea that might eventually be patentable. This material should be disclosed to one or more witnesses who should indicate in writing that they understand the purpose, method, and structure of the invention. The disclosure should be signed and dated by the inventor and the witnesses. Similarly, all subsequent work, modifications, and new ideas on the process should be recorded in chronological order in a permanent file, such as a bound notebook. Each page should be dated and signed by the person who makes the entries, and a competent witness should periodically examine, sign, and date the notes.

Infringement. The infringement of a patent may consist of making, using, or selling the invention covered by the patent without express permission of the holders. A *contributory infringement* involves the assistance or cooperation with another in the unauthorized making, using, or selling of a patented invention.

If the infringement is deliberate, the court may award the plaintiff as much as three times the actual damages caused the patentee plus three times the earned profits. In case the infringement is unintentional or innocent, the award to the plaintiff is no more than the actual loss proved.

Assignment of Patent Rights. A patentee may treat his patent as his own personal property, and he has the right to sell it outright or license it in any form he desires. Thus, the patent rights can be assigned exclusively to one concern, or the assignment of partial rights can be made. The inventor can be paid by a lump sum, a periodic payment, a per cent of the profit, a set amount for each unit produced, or in any other way that is agreeable to the parties involved. An assignment on a patent should be recorded with the U.S. Patent Office.

Contracts are frequently made between employer and employee in which the employee agrees to assign the employer all rights to patents developed through the use of the concern's facilities or information. If no definite agreement is made with respect to patent rights, an employer has a free and nonexclusive right to use any patented invention or discovery made by an employee at the expense of the employer's time and facilities. This is known as *shop rights*. Legally, the patent belongs to the employee, and he may sell the invention to others, but he cannot control in any way the shop right of the employer.

PROBLEMS

1. Prepare, in the form of a flow sheet, an outline showing the sequence of steps in the complete development of a plant for producing formaldehyde. A detailed analysis of the points to be considered at each step should be included. The outline should take the project from the initial idea to the stage where the plant is in efficient operation.

2. Using the *Chemical Abstracts* as a basis, list the original source, title, author, and brief abstract of three articles published since 1950 dealing with three different processes for producing formaldehyde.

3. List the major fields which should be considered for plant safety, and discuss the responsibilities of the design engineer in each one.

4. A process for making a single product involves reacting two liquids in a continuously agitated reactor and distilling the resulting mixture. Unused reactants are recovered as overhead and are recycled. The product is obtained in sufficiently pure form as bottoms from the distillation tower.

(*a*) Prepare a qualitative flow sheet for the process, showing all pieces of equipment.

(*b*) With cross reference to the qualitative flow sheet, list each piece of equipment and tabulate for each the information needed concerning chemicals and the process in order to design the equipment.

5. Prepare a plant layout complete with elevation drawings for the nitric acid unit shown in Figs. 10-2 and 10-3. The unit operates at a pressure of 120 psig. Use the following sizes: absorption tower, 40 ft high by 5 ft in diameter; cooler condensers, each 12 ft long by 2 ft in diameter; converter, 3 ft long by 2 ft in diameter; mixing chamber, 5 ft long by 1 ft in diameter; preoxidation chamber, 8 ft long by 3 ft in diameter; preheater, 10 ft long by 2 ft in diameter; reheater, 16 ft long by 2 ft in diameter; all other pieces of equipment except storage tanks are approximately 3 by 3 by 3 ft. Indicate location of panel boards, instruments, and control valves. Preheat the entering air by using some of the heat from the gases leaving the converter. Indicate how the gases leaving the absorption tower might be used for power recovery.

6. A nomograph for the evaluation of plant locations is presented by D. V. Bierwert and F. A. Krone, *Chem. Eng.*, **62**(12):191 (1955). Explain how this type of nomograph can be used to assist in the choice of a plant location.

7. Present drawings comparing the wiring connections used for shunt-wound and series-wound direct-current motors. Explain why the speed varies widely with load for a series-wound motor but remains essentially constant with a shunt-wound motor. Show how speed can be adjusted with a shunt-wound motor.

8. Obtain a copy of a patent dealing with a chemical process, and outline the claims presented in this patent. Indicate the method used for presenting the specifications, and explain how the inventor presented proof of his claims.

CHAPTER 11

WASTE DISPOSAL AND TREATMENT

The various waste materials produced by industrial plants may be classified in general as solid, gaseous, or liquid. Disposal of solid wastes is directly related to the problems of land pollution, while gaseous and liquid wastes contribute to air and water pollution, respectively. Although land, air, and water pollution are often considered separately, the combined and interrelated effects of all three types of pollution should be recognized.

In the early years of the chemical industry, waste disposal was given little attention, and useless products and effluents were disposed of in the cheapest and most convenient manner. In recent years, however, local, state, and national regulations have forced industrial concerns to put a large amount of effort into devising adequate methods for treating and disposing of their wastes.

Although waste disposal and treatment are generally considered as a branch of sanitary engineering, the chemical engineer cannot ignore the subject. In particular, the design engineer cannot afford to overlook the need for providing adequate facilities to handle industrial wastes, and he should immediately recognize the advisability of segregating sanitary-sewage lines from industrial-waste lines.

METHODS FOR HANDLING WASTE-DISPOSAL PROBLEMS

Eliminate at Source. The first approach to a waste-disposal problem requires careful consideration of the source of the pollution. Sometimes, a detailed study will show that the waste problem is due to operating part of the plant at overcapacity. During an emergency period, increased production demands can make it necessary to operate at capacities above the design values, and there are cases when these high rates are continued after the emergency is over. If the pollution problem is caused by operation at overcapacity, installation of additional process equipment or reduction in production rate may be cheaper and more effective than adding expensive waste-treating facilities.

A careful check should be made of all locations where wastes could inadvertently enter the sewers or discharge lines. For example, pump glands, pipe joints, relief valves, sloppy operating methods, or even indiscriminate dumping of samples down the drain can contribute to waste-disposal difficulties.

Recovery of Waste Products. Before deciding how to discard waste materials, the engineer should always consider the possibility of recovering part of the products for reuse or sale. Frequently, a company can actually save money by installing recovery facilities rather than expensive waste-treating equipment.

Regulate Waste Flow to Fit Dilution. A large percentage of complaints about pollution come after an emergency has forced a sudden release of contaminants or during certain seasons of the year, such as late summer, when the water supply may be low. A large pond or storage basin can serve effectively to store waste products until local conditions will permit release of the material with no danger of exceeding pollution limits.

Divert Wastes to Another Discharge Point. Canals or pipelines to nearby lakes, quarries, waterways, or other waste receivers can often take the load off the local outlet used for waste disposal. In this way, the waste product can be distributed so that full advantage is taken of all possible facilities for natural waste disposal.

Waste Treatment. If none of the preceding methods is capable of solving a given waste-disposal problem, waste treatment must be used. This treatment can be either chemical or physical in nature, depending upon the type of waste involved and the amount of removal necessary.

AIR AND LAND POLLUTION *

The recent difficulties encountered in the Los Angeles region due to the smog problem and the question as to how to dispose of solid and gaseous radioactive wastes has focused attention on air and land pollution. Extensive efforts have been directed toward controlling the many types of materials that contribute to air pollution. Electrostatic precipitators, venturi scrubbers, cyclones, sonic agglomerators, scrubbers, washers, and many other kinds of equipment and treating methods have been used to remove atmospheric contaminants from waste gases.

Disposal of solid waste materials on land is always complicated by the leaching action of surface waters and the possibility of underground-stream pollution. Incineration and burying in concrete-encased blocks are possible solutions for particularly dangerous wastes, and transportation to uninhabited regions is often accepted as the best solution for disposing of other types of solid wastes.

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* P. L. Magill, F. R. Holden, and C. Ackley, "Air Pollution Handbook," McGraw-Hill Book Company, Inc., New York, 1956.

L. C. McCabe, Air Pollution Review, *Ind. Eng. Chem.*, **46**:1646 (1954).

W. A. Rodger, Radioactive Wastes, *Chem. Eng. Progr.*, **50**:263 (1954).

WATER POLLUTION

The disposal of liquid industrial wastes and the related aspects of water pollution are of major importance in the chemical process industries.* Water is considered to be polluted when waste matter is introduced in amounts sufficient to make the water unsuitable for domestic supply, industrial supply, or proper support and growth of marine life. The common causes of pollution and typical contributing industries are presented in the following list:

1. Dissolved inorganic salts
   Chemical plants
   Water-softening plants
   Tanneries
2. Acids and alkalies
   Chemical plants
   Coal mines
   Steel industry
   Petroleum refineries
3. Suspended solids
   Breweries
   Distilleries
   Paper mills
4. Floating matter (oils and greases)
   Laundries
   Packinghouses
   Petroleum refineries
5. Oxygen-consuming materials
   Breweries
   Distilleries
   Laundries
   Tanneries

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* E. B. Besselievre, "Industrial Waste Treatment," McGraw-Hill Book Company, Inc., New York, 1952.

C. F. Gurnham, "Principles of Industrial Waste Treatment," John Wiley & Sons, Inc., New York, 1956.

W. Rudolfs, "Industrial Wastes," ACS Monograph No. 118, Reinhold Publishing Corporation, New York, 1953.

Symposium on Problems in Stream Pollution, *Ind. Eng. Chem.*, **48**:234–274 (1956).

B. J. McCabe and W. W. Eckenfelder, "Biological Treatment of Sewage and Industrial Wastes," Reinhold Publishing Corporation, New York, 1956.

6. Toxic materials
    - Atomic-energy plants
    - Chemical plants
    - Pulp mills
    - Electroplating shops
7. Taste- and odor-producing materials
    - Chemical plants
    - Petroleum refineries
8. High-temperature wastes
    - Electroplating shops
    - Laundries
    - Power plants

Dissolved Inorganic Salts. Addition of soluble calcium and magnesium salts to water causes an increase in hardness, with a resultant increase in tendency toward scale formation in boilers, condensers, and other heat-transfer equipment. If the water is used for domestic supply, any increase in hardness is usually undesirable, and excess amounts of anions, such as those that would be supplied by soluble chloride or bromide salts, may make the water nonpotable and sterilize the growth of organic materials. Although chemical methods and concentration methods are effective for treating some wastes of this type, the problem is usually handled by diluting the waste effluent to an acceptable concentration before the material is released to the waterways.

Acids and Alkalies. The natural alkalinity and the pH of water are reduced by the addition of acids, with a resultant increase in corrosive action and a detrimental effect on marine life. As a general observation, delicate fish, such as trout, will be adversely affected if the pH of the water is less than 5.0, and nearly all types of fish will die if the pH is less than 3.0. At the other extreme caused by addition of alkali to water, few fish can exist if the pH is greater than 9.0.

One method for treating acid and alkali waste products is by neutralization with lime or sulfuric acid. Although this method may change the pH to the desired level, it does not remove sulfate, chloride, or other ions. The possibility of recovering the acid or alkali by distillation, concentration, or in the form of a useful salt should always be considered before neutralization or dilution methods are adopted.

Suspended Solids and Floating Matter. Suspended solids in waste streams can occur as fine or colloidal materials, coarse materials that may either float or sink, and dispersed settleable solids. Floating solids and other floating materials, such as oil and grease, reduce the amount of oxygen absorbed from the air and can cause the development of anaerobic conditions in the water. Aside from the undesirable appearance of floating materials on water, the floating matter may also be a fire hazard or cause excessive corrosion and damage to pilings and boat hulls. Suspended solids can settle to the bottom of a waterway with resulting damage to bottoms marine life, tendency toward anaerobic decomposition, and interference with navigation.

Settling basins, filters, screens, and skimmers can be used to remove suspended solids or floating matter from waste effluents. In some cases, a flocculating agent, such as alum or ferric chloride, may be needed to permit rapid removal of finely divided solids.

Oxygen-consuming Materials. In the presence of the ordinary bacteria found in water, many organic materials will oxidize to form carbon dioxide, water, sulfates, and similar materials. This process consumes the oxygen dissolved in the water and may cause a depletion of dissolved oxygen.

Fresh water exposed to the atmosphere at 32°F can dissolve as much as 14 parts of oxygen per million parts of water. If the dissolved-oxygen content drops below 5 ppm, game fish will leave the area and, below 4 ppm, most fish will die. At 2 ppm, anaerobic decomposition of organic matter begins, with a resultant production of methane, hydrogen sulfide, and other foul-smelling materials.

A measure of the ability of a waste to consume the oxygen dissolved in water is known as the *biochemical oxygen demand*. The biochemical oxygen demand, or BOD, of a waste is often the primary factor that determines its importance as a pollutant. BOD of sewage, sewage effluents, polluted waters, or industrial wastes is the oxygen, reported as parts per million, consumed during a set time period by bacterial action on the decomposable organic matter.

The standard test for measuring BOD consists of diluting the waste sample with a well-aerated dilution water which has been "seeded" with a small quantity of sewage bacteria. Several diluted samples and "blanks" are sealed from contact with air and are incubated at 20°C for a standard length of time, usually 5 days. The amount of dissolved oxygen remaining in the samples and the blanks is then determined by an analytical procedure, such as the Winkler method. The difference in oxygen content of the diluted samples and the blanks is then used to find the amount of oxygen consumed by the waste sample, and the result as parts of oxygen consumed per million parts of the original waste sample is reported as BOD.*

Example 1. Measurement of BOD. The following information has been obtained during a test for the BOD of a given industrial waste: Fifteen milliliters of the waste sample was added to a 300-ml BOD bottle, and the bottle was then filled with standard dilution water seeded with sewage organisms. A second 300-ml BOD bottle was filled with the standard dilution water. After 5 days at 20°C, the blank and the diluted waste sample were analyzed for dissolved oxygen content by the sodium azide modification of the Winkler method. The blank results indicated a dissolved-oxygen content of 8.0 ppm. The results for the diluted sample showed a dissolved-oxygen content of 3.0 ppm. On the basis of the following assumptions, determine the BOD for the waste: Specific gravities of the liquids are 1.0; the waste sample contains no dissolved oxygen.

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* "Standard Methods for the Examination of Water and Sewage," 9th ed., American Public Health Association, New York, 1946.

Solution

The diluted waste sample contains 15 g of waste and 285 g of dilution water.

$$\text{Total oxygen available for consumption by waste} = \frac{(285)(8)}{1{,}000{,}000}\text{ g}$$

$$\text{Final oxygen content of diluted sample} = \frac{(300)(3)}{1{,}000{,}000}\text{ g}$$

$$\text{Oxygen depletion due to 15-g waste sample} = \frac{(285)(8)}{1{,}000{,}000} - \frac{(300)(3)}{1{,}000{,}000}\text{ g}$$

$$\begin{aligned}\text{BOD} &= \text{oxygen depletion as parts of oxygen consumed per 1,000,000 parts of waste} \\ &= \left[\frac{(285)(8)}{1{,}000{,}000} - \frac{(300)(3)}{1{,}000{,}000}\right]\frac{1{,}000{,}000}{15} = 92\end{aligned}$$

NOTE: The assumption of negligible dissolved oxygen in the waste sample is usually adequate for wastes of high BOD. However, a correction may be necessary for weak wastes or for stream samples. As an illustration, if the dissolved-oxygen content of the waste at the time of sampling had been 1.5 ppm and all other results given in the example applied, the BOD for the waste would be

$$\frac{(285)(8) + (1.5)(15) - (300)(3)}{15} = 93.5$$

Reduction in the BOD of an industrial waste is usually accomplished by an aerobic biological oxidation of the organic matter. Frequently, part of the organic matter that contributes to the BOD can be removed by the simple and direct operations of sedimentation or screening.

The trickling filter and its variant, the biofilter, are used to reduce BOD by biological oxidation. Both of these treating units consist of a large bed of stones spread over drainage tiles or other liquid-collecting systems. The liquid passes slowly through the stone bed, and bacterial action on the organic matter in the presence of oxygen causes a decrease in the BOD. The necessary bacteria are present in raw sewage. These bacteria establish themselves on the surface of the stones in the form of slimy growths, which, in the presence of oxygen, convert the undesirable organic substances into simple end products, such as carbon dioxide and water.

Toxic Materials. The presence of toxic materials, such as cyanides, metallic ions, barium chloride, chromic acid, aldehydes, germicides, dyestuffs, and radioactive isotopes, can make water unfit for domestic or industrial use. Metallic cyanides in concentrations as low as 0.3 to 0.4 ppm will kill fish by violent asphyxiation and will interfere with the digestive systems in sewage-treatment plants. Metallic ions in concentrations greater than 1 ppm cause pollution, and some metals, such as copper, are lethal to fish and act as sterilizing agents in concentrations as low as 0.3 ppm.

The heavy metals can be precipitated from wastes by the relatively simple process of adjusting the pH to about 8 or 9. If cyanides are present, it may be necessary to remove the cyanide ions before the metal will precipitate. Cyanides can be removed by chlorination under alkaline conditions or by conversion to lethal hydrogen cyanide, which can be blown off and discharged through tall stacks. The material can also be ponded in a leakproof container until the cyanide radical is consumed by oxidation and decomposition. Nonlethal ferrocyanide can be formed by treating the waste with a large excess of ferrous sulfate.

Taste- and Odor-producing Materials. Many organic compounds impart a disagreeable taste and odor to water without otherwise making the water unfit for domestic or industrial use. Perhaps one of the worst offenders of this type is dichlorophenol. The metabolism of a fish does not operate effectively to oxidize the phenolic derivatives, and dichlorophenol will accumulate in the body cells until the fish is nonpalatable.

Concentrations as low as 2 parts of dichlorophenol per billion parts of water have been prepared and tested as to taste and odor effects. The original mixture had no noticeable odor or taste; yet, after live fish were kept in the mixture for 2 weeks, the accumulation of dichlorophenol was such that the fish had a disagreeable odor and taste.

High-temperature Wastes. Sudden release of high-temperature wastes into waterways may kill sensitive fish in the immediate area. A rise in the temperature of a natural stream can cause inconvenience to downstream industries using the water as a cooling medium and will always tend to reduce the dissolved-oxygen content of the stream. If heat recovery from the waste material cannot be accomplished economically, ponding, spray systems, or dilution with colder water may be advisable.

CHAPTER 12

THE DESIGN REPORT

A successful engineer must be able to apply theoretical and practical principles in the development of ideas and methods, and he must also have the ability to express himself clearly and convincingly. During the course of a design project, the engineer must prepare many written reports in which he explains what he has done and presents his conclusions and recommendations. The decision on the advisability of continuing the project may be made on the basis of the material presented in the reports. The value of the engineer's work is measured to a large extent by the results given in his written reports and the manner in which these results are presented.

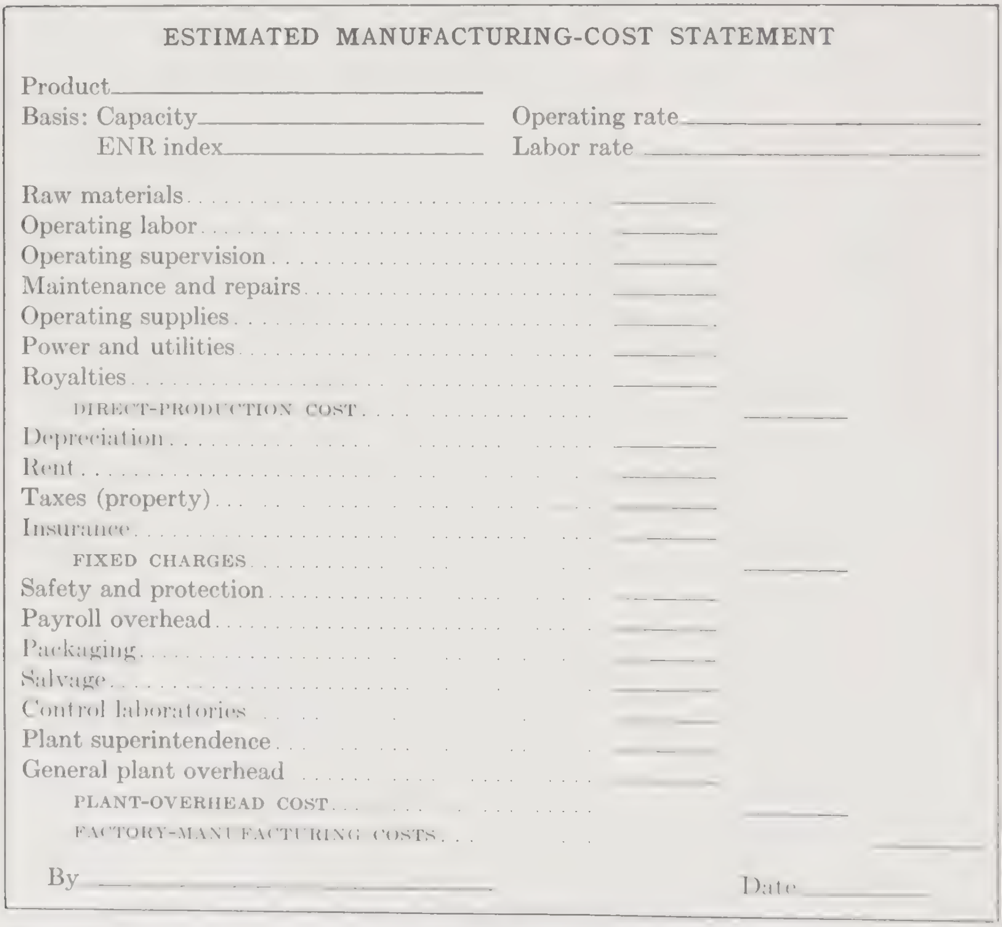
The essential purpose of any report is to pass on information to others. A good report writer never forgets the words "to others." The abilities, the functions, and the needs of the reader should be kept in mind constantly during the preparation of any type of report. Here are some questions the writer should ask himself before starting, while writing, and after finishing a report:

What is the purpose of this report?
Who will read it?
Why will they read it?
What is their function?
What technical level will they understand?
What background information do they have now?

The answers to these questions indicate the type of information that should be presented, the amount of detail required, and the most satisfactory method of presentation.

Types of Reports. The two primary types of reports can be designated as *formal* and *informal*. Formal reports are often encountered as research, development, or design reports. They present the results in considerable detail, and the writer is allowed much leeway in choosing the type of presentation. Informal reports include memorandums, letters, progress notes, survey-type results, and similar items in which the major purpose is to present a result without including detailed information. Stereotyped forms are often used for informal reports, such as those for sales, production, calculations, progress, analyses, or summarizing economic evaluations. Figures 12-1 through 12-3 present examples of stereotyped forms that can be used for presenting the summarized results of economic evaluations.

Although many general rules can be applied to the preparation of reports, it should be realized that each industrial concern has its own specifications and regulations. A stereotyped form shows exactly what information is wanted, and detailed instructions are often given for preparing other types of informal reports. Many companies have standard outlines that must be followed for formal reports. For convenience, certain arbitrary rules of rhetoric and form may be established by a particular concern. For example, periods may be required after all abbreviations, titles of articles may be required for all references, or the use of a set system of units or nomenclature may be specified.



ESTIMATED MANUFACTURING-COST STATEMENT

Product ____________________
Basis: Capacity ____________________ Operating rate ____________________
ENR index ____________________ Labor rate ____________________

Raw materials . . . . ________
Operating labor . . . . ________
Operating supervision . . . . ________
Maintenance and repairs . . . . ________
Operating supplies . . . . ________
Power and utilities . . . . ________
Royalties . . . . ________
DIRECT-PRODUCTION COST . . . . ________
Depreciation . . . . ________
Rent . . . . ________
Taxes (property) . . . . ________
Insurance . . . . ________
FIXED CHARGES . . . . ________
Safety and protection . . . . ________
Payroll overhead . . . . ________
Packaging . . . . ________
Salvage . . . . ________
Control laboratories . . . . ________
Plant superintendence . . . . ________
General plant overhead . . . . ________
PLANT-OVERHEAD COST . . . . ________
FACTORY-MANUFACTURING COSTS . . . . ________

By ____________________ Date ________

FIG. 12-1. Example of form for an informal summarizing report on factory manufacturing cost.

ESTIMATED CAPITAL-INVESTMENT STATEMENT

Product ____________________
Basis: Capacity ____________________ ENR index ____________________

Purchased equipment (delivered)	______		
Installation of equipment	______		
Insulation	______		
Instrumentation	______		
Piping	______		
Electrical installations	______		
Buildings including services	______		
Yard improvements	______		
Service facilities	______		
Land	______		
TOTAL PHYSICAL COST		______	
Engineering and construction	______	______	
DIRECT PLANT COST		______	
Contractor's fee	______		
Contingency	______	______	
FIXED-CAPITAL INVESTMENT		______	
Raw-materials inventory	______		
Product and in-process inventory	______		
Accounts receivable	______		
Cash	______		
WORKING CAPITAL		______	
TOTAL CAPITAL INVESTMENT			______

By ____________________ Date ________

Fig. 12-2. Example of form for an informal summarizing report on capital investment.

ESTIMATED INCOME AND RETURN STATEMENT

Product______________________________ Sales price______________
Basis: Capacity______________________ Operating rate___________
ENR index____________________________ Labor rate_______________

Direct production costs . . . . ________
Fixed charges . . . . ________
Plant overhead costs. . . . . ________
FACTORY-MANUFACTURING COSTS. . . . . ________
Administrative costs . . . . ________
Distribution and selling costs. . . . . ________
Research and development . . . . ________
Financing . . . . ________
GENERAL EXPENSES. ________
TOTAL PRODUCT COST . . . . ________
TOTAL INCOME . . . . ________

Fixed-capital investment______________ Working capital______________
Total-capital investment______________ Probable accuracy of estimate________
Gross earnings before taxes___________ Net profit after ___% taxes__________
Annual return on capital before taxes__________%
Annual return on capital after ___% taxes__________%

By______________________________ Date__________

FIG. 12-3. Example of form for an informal summarizing report on income and return.

ORGANIZATION OF REPORTS

The organization of a formal report requires careful sectioning and the use of sub headings in order to maintain a clear and effective presentation.* To a lesser degree, the same type of sectioning is valuable for informal reports. The following discussion applies to formal reports, but, by deleting or combining appropriate sections, the same principles can be applied to the organization of any type of report.

A complete design report consists of several essentially independent parts, with each succeeding part giving greater detail on the design and its development. A covering *Letter of Transmittal* is usually the first item in any report. After this come the *Title Page*, the *Table of Contents*, and an *Abstract* or *Summary* of the report. The *Body* of the report is next, and it includes the essential information, presented in the form of discussion, graphs, tables, and figures. The *Appendix*, at the end of the report, gives detailed information which permits complete verification of the results shown in the body. Tables of data, sample calculations, and other supplementary material are included in the Appendix. A typical outline for a design report is as follows:

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* J. R. Nelson, "Writing the Technical Report," 3d ed., McGraw-Hill Book Company, Inc., New York, 1952.

J. H. Perry, "Chemical Business Handbook," McGraw-Hill Book Company, Inc., New York, 1954.

B. H. Weil, "The Technical Report," Reinhold Publishing Corporation, New York, 1954.

ORGANIZATION OF A DESIGN REPORT

I. Letter of transmittal
    A. Indicates why report has been prepared
    B. Gives essential results that have been *specifically requested*
II. Title page
    A. Includes title of report, name of person to whom report is submitted, writer's name and organization, and date
III. Table of contents
    A. Indicates location and title of figures, tables, and all major sections
IV. Summary
    A. Briefly presents essential results and conclusions in a clear and precise manner
V. Body of report
    A. Introduction
        1. Presents a brief discussion to explain what the report is about and the reason for the report; no results are included
    B. Previous work
        1. Discusses important results obtained from literature surveys and other previous work
    C. Discussion
        1. Outlines method of attack on project
        2. Includes graphs, tables, and figures that are essential for understanding the discussion
        3. Discusses technical matters of importance
        4. Indicates assumptions made and the reasons
        5. Indicates possible sources of error
        6. Gives a general discussion of results and proposed design
    D. Final recommended design with appropriate data
        1. Drawings of proposed design
            a. Qualitative flow sheets
            b. Quantitative flow sheets
            c. Combined-detail flow sheets
        2. Tables listing equipment and specifications
        3. Tables giving material and energy balances
        4. Process economics including costs, profits, and return on investment

  - *E*. Conclusions and recommendations
    1. Presented in more detail than in Summary
  - *F*. Acknowledgment
    1. Acknowledges important assistance of others who are not listed as preparing the report
  - *G*. Table of nomenclature
    1. Sample units should be shown
  - *H*. References to literature (bibliography)
    1. Gives complete identification of literature sources referred to in the report
- VI. Appendix
  - *A*. Sample calculations
    1. One example should be presented and explained clearly for each type of calculation
  - *B*. Derivation of equations essential to understanding the report but not presented in detail in the main body of the report
  - *C*. Tables of data employed with reference to source
  - *D*. Results of laboratory tests
    1. If laboratory tests were used to obtain design data, the experimental data, apparatus and procedure description, and interpretation of the results may be included as a special appendix to the design report

Letter of Transmittal. The purpose of a letter of transmittal is to refer to the original instructions or developments that have made the report necessary. The letter should be brief, but it can call the reader's attention to certain pertinent sections of the report or give definite results which are particularly important. The writer should express any personal opinions in the letter of transmittal rather than in the report itself. Personal pronouns and an informal business style of writing may be used.

Title Page and Table of Contents. In addition to the title of the report, a title page usually indicates other basic information, such as the name and organization of the person (or persons) submitting the report and the date of submittal. A table of contents may not be necessary for a short report of only six or eight pages, but, for longer reports, it is a convenient guide for the reader and indicates the scope of the report. The titles and subheadings in the written text should be shown, as well as the appropriate page numbers. Indentations can be used to indicate the relationships of the various subheadings. A list of tables, figures, and graphs should be presented separately at the end of the table of contents.

Summary. The summary is probably the most important part of a report, since it is referred to most frequently and is often the only part of the report that is read. Its purpose is to give the reader the entire contents of the report in one or two pages. It covers all phases of the design project, but it does not go into detail on any particular phase. All statements must be concise and give a minimum of general qualitative information. The aim of the summary is to present precise quantitative information and final conclusions with no unnecessary details.

The following outline shows what should be included in a summary:

1. A statement introducing the reader to the subject matter
2. What was done and what the report covers
3. How the final results were obtained
4. The important results including quantitative information, major conclusions, and recommendations

An ideal summary can be completed on one typewritten page. If the summary must be longer than two pages, it may be advisable to precede the summary by an *abstract*, which merely indicates the subject matter, what was done, and a brief statement of the major results.

Body of the Report. The first section in the body of the report is the *introduction*. It states the purpose and scope of the report and indicates why the design project originally appeared to be feasible or necessary. The relationship of the information presented in the report to other phases of the company's operations can be covered, and the effects of future developments may be worthy of mention. References to *previous work* can be discussed in the introduction, or a separate section can be presented dealing with literature-survey results and other previous work.

A description of the methods used for developing the proposed design is presented in the next section under the heading of *discussion*. Here the writer shows the reader the methods used in reaching the final conclusions. The validity of the methods must be made apparent, but the writer should not present an annoying or distracting amount of detail. Any assumptions or limitations on the results should be discussed in this section.

The next section presents the *recommended design*, complete with figures and tables giving all necessary qualitative and quantitative data. An analysis of the cost and profit potential of the proposed process should accompany the description of the recommended design.

The body of a design report often includes a section giving a detailed discussion of all *conclusions and recommendations*. When applicable, sections covering *acknowledgment*, *table of nomenclature*, and *literature references* may be added.

Appendix. In order to make the written part of a report more readable, the details of calculation methods, experimental data, reference data, certain types of derivations, and similar items are often included as separate appendixes to the report. This information is thus available to anyone who wishes to make a complete check on the work; yet the descriptive part of the report is not made ineffective because of excess information.

PREPARING THE REPORT

The physical process of preparing a report can be divided into the following steps:

1. Define the subject matter, scope, and intended audience.
2. Prepare a skeleton outline and then a detailed outline.
3. Write the first draft.
4. Polish and improve the first draft and prepare the final form.
5. Check the written draft carefully, have the report typed, and proofread the final report.

In order to accomplish each of these steps successfully, the writer must make certain he starts the initial work on the report soon enough to do a thorough job and still meet any predetermined deadline date. Many of the figures, graphs, and tables, as well as some sections of the report, can be prepared while the design work is in progress.

Presenting the Results

Accuracy and logic must be maintained throughout any report. The writer has a moral responsibility to present his facts accurately, and he must not mislead the reader with incorrect or dubious statements. If approximations or assumptions are made, their effect on the accuracy of the results should be indicated. For example, a preliminary plant design might show that the total investment for a proposed plant is $5,500,000. This is not necessarily misleading as to the accuracy of the result, since only two significant figures are indicated. On the other hand, a proposed investment of $5,554,328 is ridiculous, and the reader knows at once that the writer did not use any type of logical reasoning in determining the accuracy of the results.

The style of writing in technical reports should be simple and straightforward. Although short sentences are preferred, variation in the sentence length is necessary in order to avoid a disjointed staccato effect. The presentation must be convincing, but it must also be devoid of distracting and unnecessary details. Flowery expressions and technical jargon are often misused by technical writers in an attempt to make their writing more interesting. Certainly, an elegant or forceful style is sometimes desirable, but the technical writer must never forget that his major purpose is to present information clearly and understandably.

Subheadings and Paragraphs. The use of effective and well-placed subheadings can improve the readability of a report. The sections and subheadings follow the logical sequence of the report outline, and they permit the reader to orient himself and prepare himself for a new subject.

Paragraphs are used to cover one general thought. A paragraph break, however, is not nearly as definite as a subheading. The length of paragraphs can vary over a wide range, but any thought worthy of a separate paragraph should require at least two sentences. Long paragraphs are a strain on the reader, and the writer who consistently uses paragraphs longer than 10 to 12 typed lines will have difficulty in holding his readers' attention.

Tables. The effective use of tables can save many words, especially if quantitative results are involved. Tables are included in the body of the report only if they are essential to the understanding of the written text. Any type of tabulated data that is not directly related to the discussion should be located in the appendix.

Every table requires a title, and the headings for each column should be self-explanatory. If numbers are used, the correct units must be shown in the column heading or with the first number in the column. A table should never be presented on two pages unless the amount of data makes a break absolutely necessary.

Graphs. In comparison with tables, which present definite numerical values, graphs serve to show trends or comparisons. The interpretation of results is often simplified for the reader if he can see the tabulated information presented in graphical form.

If possible, the experimental or calculated points on which a curve is based should be shown on the plot. These points can be represented by large dots, small circles, squares, triangles, or some other identifying symbol. The most probable smooth curve can be drawn on the basis of the plotted points, or a broken line connecting each point may be more appropriate. In any case, the curve should not extend through the open symbols representing the data points. If extrapolation or interpolation of the curve is doubtful, the uncertain region can be designated by a dotted or dashed line.

The ordinate and the abscissa must be labeled clearly, and any nomenclature used should be defined on the graph or in the body of the report. If numerical values are presented, the appropriate units are shown immediately after the labels on the ordinate and abscissa. Restrictions on the plotted information should be indicated on the graph itself or with the title.

The title of the graph must be explicit but not obvious. For example, a log-log plot of temperature versus the vapor pressure of pure glycerol should not be entitled "Log-Log Plot of Temperature versus Vapor Pressure for Pure Glycerol." A much better title, although still somewhat obvious, would be "The Effect of Temperature on the Vapor Pressure of Pure Glycerol."

Some additional suggestions for the preparation of graphs follow:

1. The independent or controlled variable should be plotted as the abscissa, and the variable that is being determined should be plotted as the ordinate.

2. Permit sufficient space between grid elements to prevent a cluttered appearance (ordinarily, two to four grid lines per inch are adequate).

3. Use coordinate scales that give good proportionment of the curve over the entire plot, but do not distort the apparent accuracy of the results.

4. The values assigned to the grids should permit easy and convenient interpolation.

5. If possible, the label on the vertical axis should be placed in a horizontal position to permit easier reading.

6. Unless families of curves are involved, it is advisable to limit the number of curves on any one plot to three or less.

7. The curve should be drawn as the heaviest line on the plot, and the coordinate axes should be heavier than the grid lines.

Illustrations. Flow diagrams, photographs, line drawings of equipment, and other types of illustrations may be a necessary part of a report. They can be inserted in the body of the text or included in the appendix. Complete flow diagrams, drawn on oversize paper, and other large drawings are often folded and inserted in an envelope at the end of the report.

References to Literature. The original sources of any literature referred to in the report should be listed at the end of the body of the report. The references are usually tabulated and numbered in alphabetical order on the basis of the first author's surname, although the listing is occasionally based on the order of appearance in the report.

When a literature reference is cited in the written text, the last name of the author is mentioned and the bibliographical identification is shown by a raised number after the author's name or at the end of the sentence. An underlined number in parentheses may be used in place of the raised number, if desired.

The bibliography should give the following information:

1. For journal articles—(a) authors' names, followed by initials, (b) journal, abbreviated to conform to the "List of Periodicals" as established by *Chemical Abstracts*, (c) volume number, (d) issue number, if necessary, (e) page numbers, and (f) year (in parentheses). The title of the article is usually omitted. Issue number is omitted if paging is on a yearly basis. The date is sometimes included with the year in place of the issue number.

Amos, J. L., and Roche, A. F., Ind. Eng. Chem., 47:2441-2444 (1955).
Cannon, M. R., Oil Gas J., 54:68 (Jan. 23, 1956).
Skiba, E. J., Chem. Eng., 61(12):182-6 (1954).

2. For single publications, as books, theses, or pamphlets—(a) authors' names, followed by initials, (b) title (in quotation marks), (c) edition (if more than one has appeared), (d) volume (if there is more than one), (e) publisher, (f) place of publication, and (g) year of publication. The

chapter or page number is often listed just before the publisher's name. Titles of theses are often omitted.

Nelson, J. R., "Writing the Technical Report," 3d ed., p. 284, McGraw-Hill Book Company, Inc., New York, 1952.

Perkins, A. S., M.S. Thesis in Chem. Eng., Univ. of Illinois, Urbana, Ill., 1955.

3. For unknown or unnamed authors—(*a*) alphabetize by the journal or organization publishing the information.

Chem. *Eng*., *61*(12):132 (1954).

4. For patents—(*a*) patentees' names, followed by initials, and assignee (if any) in parentheses, (*b*) country granting patent and number, and (*c*) date issued (in parentheses).

Froyan, J. E. (to Phillips Petroleum Co.), U.S. Patent 2,615,010 (Oct. 21, 1952).

5. For unpublished information—(*a*) "in press" means formally accepted for publication by the indicated journal or publisher; (*b*) the use of "private communication" and "unpublished data" is not recommended unless absolutely necessary, since the reader may find it impossible to locate the original material.

Treybal, R. E., *Ind*. *Eng*. *Chem*., in press (1955).

Sample Calculations. The general method used in developing the proposed design is discussed in the body of the report, but detailed calculation methods are not presented in this section. Instead, sample calculations are given in the appendix. One example should be shown for each type of calculation, and sufficient detail must be included to permit the reader to follow each step. The particular conditions chosen for the sample calculations must be designated. The data on which the calculations are based should be listed in detail at the beginning of the section, even though these same data may be available through reference to one of the tables presented with the report.

Mechanical Details. The final report should be submitted in a neat and businesslike form. Formal reports are usually bound with a heavy cover, and the information shown on the title page is repeated on the cover. If paper fasteners are used for binding in a folder, the pages should be attached only to the back cover.

The report should be typed on a good grade of paper with a margin of at least 1 in. on all sides. Normally, only one side of the page is used and all material, except the letter of transmittal, footnotes, and long quotations, is double-spaced. Starting with the summary, all pages, including graphs, illustrations, and tables, should be numbered in sequence.

Written material on graphs and illustrations may be typed or lettered neatly in ink. If hand lettering is required, best results are obtained with an instrument such as a LeRoy or Wrico guide.

Short equations can sometimes be included directly in the written text if the equation is not numbered. In general, however, equations are centered on the page and given a separate line, with the equation number appearing at the right-hand margin of the page. Explanation of the symbols used can be presented immediately following the equation.

Proofreading and Checking. Before final submittal, the completed report should be read carefully and checked for typographical errors, consistency of data quoted in the text with those presented in tables and graphs, grammatical errors, spelling errors, and similar obvious mistakes. If excessive corrections or changes are necessary, the appearance of the report must be considered and some sections may need to be retyped.

Nomenclature. If many different symbols are used repeatedly throughout a report, a table of nomenclature, showing the symbols, meanings, and sample units, should be included in the report. Each symbol can be defined when it first appears in the written text. If this is not done, a reference to the table of nomenclature should be given with the first equation.

Ordinarily, the same symbol is used for a given physical quantity regardless of its units. Subscripts, superscripts, and lower- and upper-case letters can be employed to give special meanings. The nomenclature should be consistent with common usage (a list of recommended symbols for chemical engineering quantities is presented in Table 1 [*]).

TABLE 1. LETTER SYMBOLS FOR CHEMICAL ENGINEERING

Item	*Symbol*	*Sample units (English system)*
	General	
Acceleration	a	(ft/sec)/sec
Acceleration of gravity	g	(ft/sec)/sec
Activity	a	
Activity coefficient	γ (gamma)	
Angle	α (alpha), θ (theta), ϕ (phi)	degrees, radians
Area	A, S	sq ft
Base of natural logarithms	e	
Breadth, width	b	ft
Coefficient, in general	C	
Coefficient of linear expansion	α (alpha)	(ft/ft)/°F

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[*] The nomenclature presented in Table 1 is consistent with the recommendations of the American Standards Association's "Letter Symbols for Chemical Engineering," Z10.12—1946. See M. Souders, *Chem. Eng. Progr.*, **52**:255 (1956).

TABLE 1. LETTER SYMBOLS FOR CHEMICAL ENGINEERING (*Continued*)

Item	*Symbol*	*Sample units (English system)*
Coefficient of volumetric expansion	β (beta)	(cu ft/cu ft)/°F
Compressibility factor	z	pV/RT
Concentration, volumetric	c	lb/cu ft or lb mole/cu ft
Conversion factor in Newton's law of motion	g_c	(ft)(lb mass)/(sec)(sec)(lb force)
Cross section	S, A	sq ft
Density	ρ (rho)	lb/cu ft
Diameter	D	ft
Difference, finite	Δ (capital delta)	
Differential operator	d	
Diffusivity, thermal	α (alpha)	sq ft/hr
Diffusivity of vapor	D_v	sq ft/hr
Efficiency	η (eta)	
Energy in general	E	Btu, Btu/lb mole
Enthalpy	H	Btu, Btu/lb mole
Enthalpy, per unit weight	h, i	Btu/lb
Entropy	S	Btu/°R, Btu/(lb mole)(°R)
Entropy, per unit weight	s	Btu/(lb)(°R)
Fluidity	$1/\mu$	(sec)(ft)/lb
Force, total load	F	lb force
Free energy, Gibbs	G F	$(H - TS)$, Btu, Btu/lb mole
Free energy, Helmholtz	A	$(U - TS)$ Btu, Btu/lb mole
Fugacity	f	lb force/sq ft. atm
Function	ϕ, ψ, χ (phi, psi, chi)	
Gas constant, universal	R	(lb force/sq ft)(cu ft)/(lb mole)(°R)
Internal energy	U	Btu, Btu/lb mole
Internal energy, per unit weight	u	Btu/lb
Latent heat of vaporization	λ (lambda), h_{fg}	Btu/lb
Length	L	ft
Mass	m	lb
Mechanical equivalent of heat	J	(ft)(lb force)/Btu
Molecular weight	M	lb
Moment of inertia	I	(lb mass)(ft)^2, also (ft)^4
Power	P	(ft)(lb force)/sec
Pressure	p	lb force/sq ft, atm
Quantity of matter, weight	W	lb
Radius	r	ft
Rate of rotation	n	rev/min
Solid angle	ω (omega)	
Specific heat	c	dimensionless or Btu/(lb)(°F)
Specific heat at constant pressure	c_p	dimensionless or Btu/(lb)(°F)
Specific heat at constant volume	c_v	dimensionless or Btu/(lb)(°F)
Specific heats ratio of	k, κ (kappa), γ (gamma)	c_p/c

TABLE 1. LETTER SYMBOLS FOR CHEMICAL ENGINEERING (*Continued*)

Item	*Symbol*	*Sample units (English system)*
Specific volume	v	cu ft/lb
Surface per unit volume	a	sq ft/cu ft
Surface tension	σ (sigma)	lb force/ft
Temperature	t	°F, °C
Temperature, absolute	T	°R, °K
Thermal conductivity	k	Btu/(hr)(sq ft)(°F/ft)
Time	t, τ (tau), θ (theta)	sec, hr
Velocity, angular	ω (omega)	radians/sec
Viscosity, absolute	μ (mu)	lb/(sec)(ft)
Viscosity, kinematic	ν (nu)	sq ft/sec
Volume, total or per mole	V	cu ft, cu ft/lb mole
Work	W	Btu, (ft)(lb force)
Work, external	W_e	Btu, (ft)(lb force)
	Flow of Fluids	
Coefficient, of discharge, etc.	C	
Depth	y	ft
Distance above datum plane	Z	ft
Distance in direction of flow	x	ft
Friction, in energy balance	F	(ft)(lb force)/lb mass
Friction factor, Fanning	$\mathfrak{f}$	$(F = 2\mathfrak{f}V^2L/g_cD)$
Hydraulic radius	R_H	ft, sq ft/ft
Mass flow rate	w	lb/hr
Mass velocity	G	lb/(hr)(sq ft)
Rate of flow, volumetric	q	cu ft/hr
Tractive force per unit area	τ (tau)	lb force/sq ft
Velocity, acoustic	V_a, c	ft/sec
Velocity, average	V	ft/sec
Velocity, local	u	ft/sec
Weight rate of flow per unit of breadth	Γ (capital gamma)	lb/(hr)(ft), lb/(sec)(ft)
	Heat Transmission	
Absorptivity (for radiation)	α (alpha)	
Coefficient of heat transfer, individual	h	Btu/(hr)(sq ft)(°F)
Conductance	$1/R$, C	Btu/(hr)(°F)
Emissivity (for radiation)	ϵ (epsilon)	
Film thickness, effective	B	ft
Fraction by volume	x_v	
Fraction by weight	x_w	
Heat-transfer coefficient, over-all	U	Btu/(hr)(sq ft)(°F)
Heat-transfer factor	j	$(h/cG)\phi(c\mu/k)$
Quantity of heat transferred	Q	Btu

TABLE 1. LETTER SYMBOLS FOR CHEMICAL ENGINEERING (*Continued*)

Item	*Symbol*	*Sample units (English system)*
Radiation, intensity of	N	Btu/(hr)(sq ft)
Rate of heat transfer	q	Btu/hr
Resistance, thermal	R	°F/(Btu/hr)
Stefan-Boltzmann constant	σ (sigma)	
Unit conductance	$1/RA$	Btu/(hr)(sq ft)(°F)
Evaporation, Humidification, and Dehumidification		
Humid heat	c_s	Btu/(lb dry air)(°F)
Humid volume	v_H	cu ft/lb dry air
Humidity	H	lb/lb dry air
Percentage humidity	H_P	
Relative humidity	H_R	
Gas Absorption and Extraction		
Height of transfer unit, "*HTU*"	H_t, Z_t	ft
Henry's law constant, c/p	H	(lb moles/cu ft)/atm
Mass transfer coefficient, individual	k	lb moles/(hr)(sq ft)(atm)
Gas film	k_G	lb moles/(hr)(sq ft)(atm)
Liquid film	k_L	lb moles/(hr)(sq ft)(lb mole/cu ft)
Mass transfer coefficient, over-all	K	lb moles/(hr)(sq ft)(atm)
On gas-film basis	K_G	lb moles/(hr)(sq ft)(atm)
On liquid-film basis	K_L	lb moles/(hr)(sq ft)(lb mole/cu ft)
Mass velocity of liquid	L	lb/(hr)(sq ft)
Mole fraction, in liquid	x	
Mole fraction, in vapor	y	
Mole fraction in vapor, equilibrium value	y^*	
Mole ratio, in liquid	X	
Mole ratio, in vapor	Y	
Rate of transfer	N	lb moles/hr
Slope of equilibrium curve	m	dy^*/dx
"Transfer units," number of	N_t	
Distillation		
Distillate rate	D	lb moles/hr
Entrainment ratio	E	lb/lb, lb moles/lb mole
Equilibrium constant, $y = Kx$	K, K^*	
Feed rate	F	lb moles/hr
Height equivalent to a theoretical plate, "*HETP*"	H_p	ft
Liquid rate	L	lb moles/hr
Above feed	L_n	lb moles/hr
Below feed	L_m	lb moles/hr
Plates, number of	N_p	

TABLE 1. LETTER SYMBOLS FOR CHEMICAL ENGINEERING (*Continued*)

Item	*Symbol*	*Sample units (English system)*
Reflux ratio	R	Use R_D for L/D, and R_V for L/V
Relative volatility	α (alpha)	$\alpha_{AB} = (y_A{}^*/x_A)/(y_B{}^*/x_B)$
Residue, waste, bottoms	W, B	lb moles/hr
Thermal condition of feed	q	$(L_m - L_n)/F$, $1 + (V_m - V_n)/F$
Vapor rate	V	lb moles/hr
Above feed	V_n	lb moles/hr
Below feed	V_m	lb moles/hr
Drying		
Equilibrium moisture content	T_E	lb/lb
Free moisture content	W	lb/lb
Production rate	R	lb/hr
Filtration		
Equivalent resistance of cloth	r	
Exponent of compressibility of cake	s	
Specific cake resistance	α (alpha)	
Engineering Economics		
Capitalized cost	K	\$
Cost, in general	C, c	\$, \$/yr, \$/unit
Declining-balance factor	$\mathfrak{f}$	
Depreciation	d	\$/yr
Fixed costs	C_F	\$/yr
Interest rate	i	
Periodic payments in an ordinary annuity	R	\$/period
Principal or present value	P	\$
Service life	n	yr
Value, asset	V_a	\$
Value, original	V	\$
Value, salvage	V_s	\$
Dimensionless Numbers Used in Chemical Engineering		
Condensation number	N_{Co}	$(h/k)(\mu^2/\rho^2 g)^{1/3}$
Froude number	N_{Fr}	V^2/gD
Graetz number	N_{Gz}	wc/kL
Grashof number	N_{Gr}	$L^3\rho^2\beta g\ \Delta t/\mu^2$
Mach number	N_{Ma}	V/V_a
Nusselt number	N_{Nu}	hD/k
Peclet number	N_{Pe}	$DV\rho c/k$
Prandtl number	N_{Pr}	$c\mu/k$
Reynolds number	N_{Re}	$DV\rho/\mu$
Schmidt number	N_{Sc}	$\mu/\rho D_v$
Stanton number	N_{St}	$h/cV\rho$

Abbreviations. Time and space can be saved by the use of abbreviations, but the writer must be certain the reader knows what is meant. Unless the abbreviation is standard, the meaning should be explained the first time it is used. The following rules are generally applicable for the use of abbreviations:

1. Abbreviations are acceptable in tables, graphs, and illustrations when space limitations make them desirable.
2. Abbreviations are normally acceptable in the text only when preceded by a number [3 ft/sec (three feet per second)].
3. Periods may be omitted after abbreviations for common scientific and engineering terms, except when the abbreviation forms another word (e.g., in. for inch).
4. The plural of an abbreviation is the same as the singular (pounds—lb).
5. The abbreviation for a noun derived from a verb is formed by adding *n* (concentration—concn).
6. The abbreviation for the past tense is formed by adding *d* (concentrated—concd).
7. The abbreviation for the participle is formed by adding *g* (concentrating—concg).

Examples of accepted abbreviations are shown in Table 2.

TABLE 2. ACCEPTED ABBREVIATIONS

American Chemical Society	ACS
American Institute of Chemical Engineers	AIChE
American Iron and Steel Institute	AISI
American Petroleum Institute	API
American Society of Mechanical Engineers	ASME
American Society for Testing Materials	ASTM
American wire gauge	AWG
Ampere	amp
Angstrom	A.
Atmosphere	atm
Average	avg
Barrel	bbl
Baumé	Bé
Biochemical oxygen demand	BOD
Boiling point	bp
Bottoms	btms
British thermal unit	Btu
Brown and Sharpe gauge number	B&S
Calorie	cal
Capacity	cap.
Catalytic	cat.
Centigrade	C
Centigram	cg
Centimeter	cm
Centipoise	cp
Centistoke	cs
Chemically pure	CP
Concentrate	conc
Critical	crit
Cubic	cu
Cubic centimeter	cc
Cubic foot	cu ft or ft^3
Cubic foot per minute	cfm
Cubic foot per second	cfs
Cubic inch	cu in. or in.^{3}
Degree	deg or °
Diameter	diam
Dilute	dil
Distill or distillate	dist
Efficiency	eff
Electromotive force	emf
Equivalent	equiv
Ethyl	Et

TABLE 2. ACCEPTED ABBREVIATIONS (*Continued*)

Evaporate	evap
Experiment	expt
Experimental	exptl
Extract	ext
Feet per minute	fpm or ft/min
Figure	fig.
Foot	ft
Foot pound	ft-lb
Gallon	gal
Gallons per minute	gpm or gal/min
Grain	spell out
Gram	gm (sometimes g) or spell out
Height equivalent to a theoretical plate	HETP
Height of a transfer unit	HTU
Horsepower	hp
Hour	hr
Hundredweight (100 lb)	cwt
Inch	in.
Inside diameter	ID or i.d.
Insoluble	insol
Kilogram	kg
Kilometer	km
Kilovolt	kv
Kilowatt	kw
Kilowatt-hour	kwhr
Liquid	liq
Liter	l or spell out
Logarithm (base 10)	log
Logarithm (base *e*)	ln
Maximum	max
Melting point	mp
Meter	m
Methyl	Me
Micron	μ or mu
Mile	mi
Miles per hour	mph
Milliampere	ma
Million electron volts	mev
Millivolt	mv
Minute	min
Molecular	mol
Ounce	oz
Outside diameter	OD or o.d.
Overhead	ovhd
Page	p.
Pages	pp.
Parts per million	ppm
Pint	pt
Pound	lb
Pound centigrade unit	Pcu
Pounds per cubic foot	lb/cu ft or lb/ft^3
Pounds per square foot	lb/sq ft or lb/ft^2
Pounds per square inch	psi
Pounds per square inch absolute	psia
Pounds per square inch gauge	psig
Quart	qt
Refractive index	RI or *n*
Revolutions per minute	rpm
Saybolt Universal seconds	SUS
Second	sec
Society of Automotive Engineers	SAE
Soluble	sol
Solution	soln
Specific gravity	sp gr
Specific heat	sp ht
Square	sq
Square foot	sq ft or ft^2
Standard	std
Standard temperature and pressure	STP
Tank	tk
Technical	tech
Temperature	temp
Tetraethyl lead	TEL
Thousand	M
Ton	spell out
Tubular Exchangers Manufacturers Association	TEMA
Volt	v
Volt-ampere	va
Volume	vol
Watt	w
Watthour	whr
Weight	wt
Yard	yd

RHETORIC

Correct grammar, punctuation, and style of writing are obvious requirements for any report. Many engineers, however, submit unimpressive reports because they do not concern themselves with the formal style of writing required in technical reports. This section deals with some of the restrictions placed on formal writing and presents a discussion of common errors.*

Personal Pronouns. The use of personal pronouns should be avoided in technical writing. Many writers eliminate the use of personal pronouns by resorting to the passive voice. This is certainly acceptable, but, when applicable, the active voice gives the writing a less stilted style. For example, instead of saying "We designed the absorption tower on the basis of . . . ," a more acceptable form would be "The absorption tower was designed on the basis of . . ." or "The basis for the absorption-tower design was. . . ."

The pronoun "one" is sometimes used in technical writing. In formal writing, however, it should be avoided or, at most, employed only occasionally.

Tenses. Both past and present tenses are commonly used in report writing; however, tenses should not be switched in one paragraph or in one section unless the meaning of the written material requires the change. General truths that are not limited by time are stated in the present tense, while references to a particular event in the past are reported in the past tense (e.g., "The specific gravity of mercury is 13.6." "The experiment was performed . . .").

Diction. Contractions such as "don't" and "can't" are seldom used in technical writing, and informal or colloquial words should be avoided. Humorous or witty statements are out of place in a technical report, even though the writer may feel they are justified because they can stimulate interest. Too often, the reader will be devoid of a sense of humor, particularly when he is involved in the serious business of digesting the contents of a technical report. A good report is made interesting by clarity of expression, skillful organization, and the significance of its contents.

Singular and Plural. Many writers have difficulty in determining if a verb should be singular or plural. This is especially true when a qualifying phrase separates the subject and its verb. For example, "A complete list of the results *is* (not *are*) given in the appendix."

Certain nouns, such as "number," "none," and "series," can be either singular or plural. As a general rule, the verb should be singular if the subject is viewed as a unit ("The number of engineers in the United States *is* increasing") and plural if the things involved are considered separately ("A number of the men *are* dissatisfied"). Similarly, the following sentences are correct: "*Thirty thousand gallons was* produced in *two* hours." "The tests show that *18* batches *were* run at the wrong temperature."

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* J. M. Kierzek, "The Macmillan Handbook of English," rev. ed., The Macmillan Company, New York, 1947.

Dangling Modifiers. The technical writer should avoid dangling modifiers that cannot be associated directly with the words they modify. For example, the sentence "Finding the results were inconclusive, the project was abandoned" could be rewritten correctly as "Finding the results were inconclusive, the investigators abandoned the project."

Poor construction caused by dangling modifiers often arises from retention of the personal viewpoint, even though personal pronouns are eliminated. The writer should analyze his work carefully and make certain the association between a modifying phrase and the words referred to is clear.

Compound Adjectives. Nouns are often used as adjectives in scientific writing. This practice is acceptable; however, the writer must use it in moderation. A sentence including "a centrally located natural gas production plant site is . . ." should certainly be revised. Prepositional clauses are often used to eliminate a series of compound adjectives.

Hyphens are employed to connect words that are compounded into adjectives—for example, "a hot-wire anemometer," "a high-pressure line"—but no hyphen appears in "a highly sensitive element."

Split Infinitives. Split infinitives are acceptable in some types of writing, but they should be avoided in technical reports. A split infinitive bothers many readers, and it frequently results in misplaced emphasis. Instead of "The supervisor intended to carefully check the data," the sentence should be "The supervisor intended to check the data carefully."

That—Which. Many technical writers tend to overwork the word *that*. Substitution of the word *which* for *that* is often acceptable, even though a strict grammatical interpretation would require repetition of *that*. The general distinction between the pronouns "that" and "which" can be stated as follows: *That* is used when the clause it introduces is necessary to define the meaning of its antecedent; *which* introduces some additional or incidental information.

Comments on Common Errors

1. The word *data* is usually plural. Say "data are," not "data is."
2. "Balance" should not be used when "remainder" is meant.
3. Use "different from" instead of "different than."
4. The word "farther" refers to distance, and "further" indicates "in addition to."
5. "Affect," as a verb, means "to influence." It should never be confused with the noun "effect," which means "result."
6. "Due to" should be avoided when "because of" can be used.

7. Use "fewer" when referring to numbers and "less" when referring to quantity or degree.

CHECK LIST FOR THE FINAL REPORT

Before submitting the final draft, the writer should make a critical analysis of his report. Following is a list of questions the writer should ask himself when he evaluates the report. These questions cover the important considerations in report writing, and they can serve as a guide for both experienced and inexperienced writers.

1. Does the report fulfill its purpose?
2. Will it be understandable to the principal readers?
3. Does the report attempt to cover too broad a subject?
4. Is sufficient information presented?
5. Is too much detail included in the body of the report?
6. Are the objectives stated clearly?
7. Is the reason for the report indicated?
8. Is the summary concise? Is it clear? Does it give the important results, conclusions, and recommendations? Is it a true summary of the entire report?
9. Is there an adequate description of the work done?
10. Are the important assumptions and the degree of accuracy indicated?
11. Are the conclusions and recommendations valid?
12. Are sufficient data included to support the conclusions and recommendations?
13. Have previous data and earlier studies in the field been considered?
14. Is the report well organized?
15. Is the style of writing readable and interesting?
16. Has the manuscript been rewritten and edited ruthlessly?
17. Is the appendix complete?
18. Are tables, graphs, and illustrations presented in a neat, readable, and organized form? Is all necessary information shown?
19. Has the report been proofread? Are pages, tables, and figures numbered correctly?
20. Is the report ready for submittal on time?

PROBLEMS

1. Prepare a skeleton outline and a detailed outline for a final report on the detailed-estimate design of a distillation unit. The unit is to be used for recovering methanol from a by-product containing water and methanol. In the past, this by-product has been sold to another concern, but the head of the engineering-development group feels that the recovery should be accomplished at his own plant. The report will be examined

by the head of the engineering-development group and will then be submitted to the plant management for final approval.

2. List ten words you often misspell and five grammatical errors you occasionally make in formal writing.

Correct the following sentences:

3. "Using the mass transfer coefficients and other physical data, Schmidt and Nusselt numbers were calculated for each experiment."

4. "The excellent agreement between the experimental and theoretical values substantiate the validity of the assumptions."

5. "This property makes the packing more efficient than any packing."

6. "He is an engineer with good theoretical training and acquainted with industrial problems."

7. "Wrought iron is equally as good as stainless steel because no temperatures will be used at above 70°F."

8. "The pressure has got to be maintained constant or the tank will not empty out at a constant rate."

Interpret, rewrite, and improve the following:

9. "The purchasing division has contracted with the X Chemical Company to supply 20,000 lb of chemical A which corresponds closely to the specifications presented and 10,000 lb of chemical E."

10. "A more rigorous derivation would be extremely complicated and would hardly be justified in view of the uncertainties existing with respect to basic information necessary for practical applications of the results."

11. "An important factor in relation to safety precautions is first and foremost giving to workmen some kind of a clear and definite instruction along the line of not coming into the radioactive areas in connection with their work."

CHAPTER 13

EQUIPMENT DESIGN AND FABRICATION

The goal of a "plant design" is to develop and present a complete plant that can operate on an effective industrial basis. To achieve this goal, the design engineer must be able to combine many separate units or pieces of equipment into one smoothly operating plant. If the final plant is to be successful, each piece of equipment must be capable of performing its necessary function. The design of equipment, therefore, is an essential part of a plant design.

The design engineer must accept the responsibility of preparing the specifications for individual pieces of equipment. He should be acquainted with methods for fabricating different types of equipment, and he needs to recognize the importance of choosing appropriate materials of construction. Design data must be developed, giving sizes, operating conditions, number and location of openings, types of flanges and heads, codes, variation allowances, and other information. Many of the machine-design details are handled by the fabricators, but the chemical engineer must supply the basic design information.

Specifications

A generalization for equipment design is that standard equipment should be selected whenever possible. If the equipment is standard, the manufacturer may have the desired size in stock. In any case, the manufacturer can usually quote a lower price and give better guarantees for standard equipment than for special equipment.

The design engineer cannot be an expert on all the types of equipment used in industrial plants. He should, therefore, make good use of the experience of others. Much valuable information can be obtained from equipment manufacturers who specialize in particular types of equipment.

Before a manufacturer is contacted, the engineer should evaluate his needs and prepare at least a preliminary specification sheet for the equipment. This preliminary specification sheet can be used by the engineer as a basis for the preparation of the final specifications, or it can be sent to a manufacturer with a request for suggestions and fabrication information. Preliminary specifications for equipment should show the following:

1. Identification
2. Function
3. Operation
4. Materials handled
5. Basic design data
6. Essential controls
7. Insulation requirements
8. Allowable tolerances
9. Special information and details pertinent to the particular equipment, such as materials of construction including gaskets, installation, necessary delivery date, supports, and special design details or comments

Final specifications can be prepared by the design engineer, but he must be careful not to include too many unnecessary restrictions. The engineer should allow the potential manufacturers or fabricators to make suggestions before he prepares detailed specifications. In this way, the final design can include small changes that reduce the first cost with no decrease in the effectiveness of the equipment. For example, the tubes in standard heat exchangers are usually 8, 12, 16, or 20 ft long, and these lengths are ordinarily kept in stock by manufacturers and maintenance departments. If a design specification called for tubes 15 ft long, the manufacturer would probably use 16-ft tubes cut off to the specified length. Thus, an increase from 15 to 16 ft for the specified tube length could cause a reduction in the total cost for the unit, because the labor charge for cutting the standard-length tubes would be eliminated. In addition, replacement of tubes might become necessary after the heat exchanger has been in use, and the replacement costs with 16-ft tubes would probably be less than with 15-ft tubes.

Figures 13-1 through 13-4 show typical types of specification sheets for equipment. These sheets apply for the normal type of equipment encountered by a chemical engineer in design work. The details of mechanical design, such as shell or head thicknesses, are not included, since they do not have a direct effect on the performance of the equipment. However, for certain types of equipment involving unusual or extreme operating conditions, the design engineer may need to extend the specifications to include additional details of the mechanical design.* Locations and sizes of outlets, supports, and other essential fabrication information can be presented with the specifications in the form of comments or drawings.

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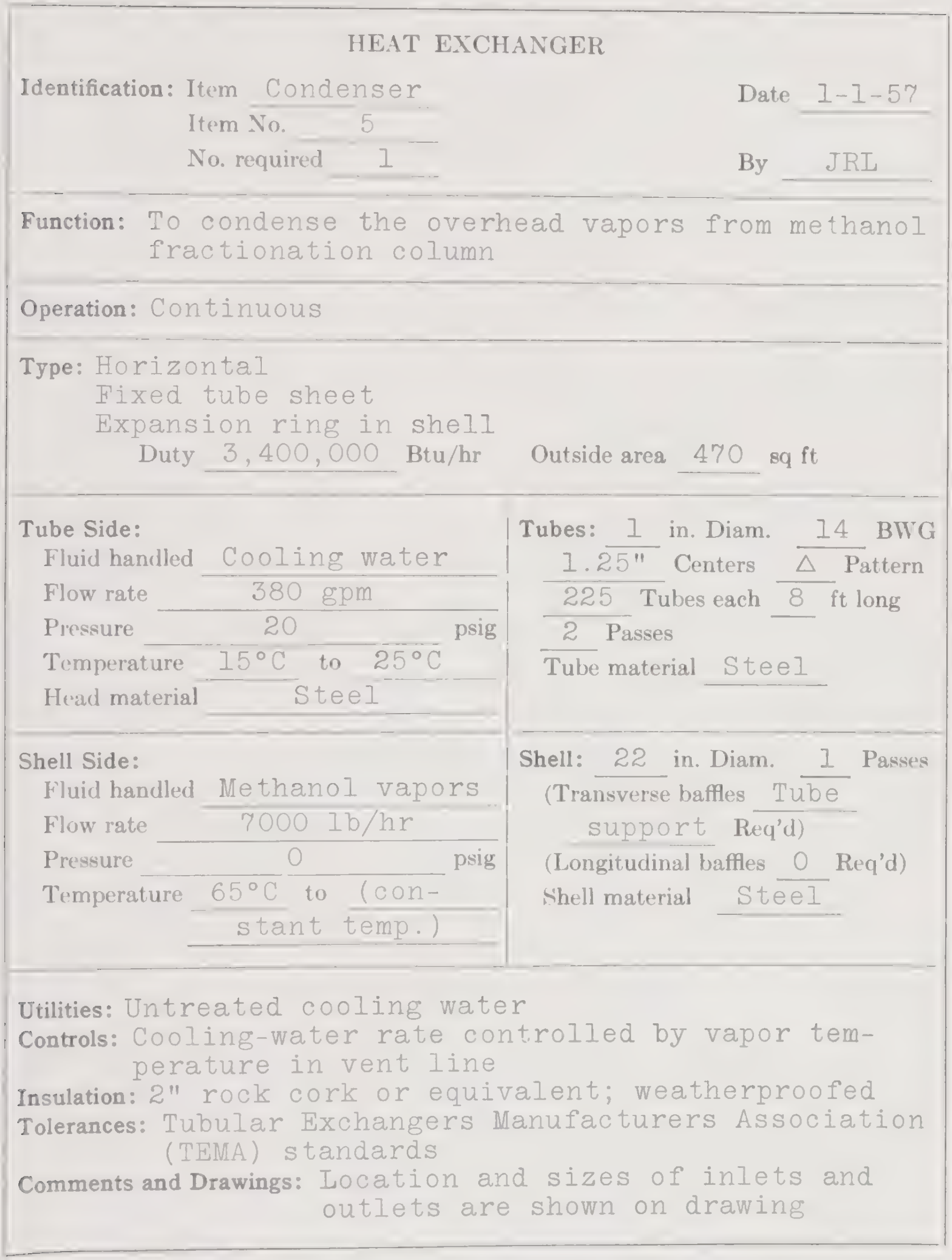
* For details on mechanical-design methods, see H. C. Hesse and J. H. Rushton, "Process Equipment Design," D. Van Nostrand Company, Inc., Princeton, N.J., 1945



HEAT EXCHANGER

Identification: Item Condenser
Item No. 5
No. required 1
Date 1-1-57
By JRL

Function: To condense the overhead vapors from methanol fractionation column

Operation: Continuous

Type: Horizontal
Fixed tube sheet
Expansion ring in shell
Duty 3,400,000 Btu/hr Outside area 470 sq ft

Tube Side:
Fluid handled Cooling water
Flow rate 380 gpm
Pressure 20 psig
Temperature 15°C to 25°C
Head material Steel

Tubes: 1 in. Diam. 14 BWG
1.25" Centers △ Pattern
225 Tubes each 8 ft long
2 Passes
Tube material Steel

Shell Side:
Fluid handled Methanol vapors
Flow rate 7000 lb/hr
Pressure 0 psig
Temperature 65°C to (constant temp.)

Shell: 22 in. Diam. 1 Passes
(Transverse baffles Tube support Req'd)
(Longitudinal baffles 0 Req'd)
Shell material Steel

Utilities: Untreated cooling water
Controls: Cooling-water rate controlled by vapor temperature in vent line
Insulation: 2" rock cork or equivalent; weatherproofed
Tolerances: Tubular Exchangers Manufacturers Association (TEMA) standards
Comments and Drawings: Location and sizes of inlets and outlets are shown on drawing

FIG. 13-1. Specification sheet for heat exchangers.

STORAGE TANK

Identification: Item ____________ Date ____________
Item No. ________
No. required ________ By ____________

Function:

Operation:

Materials Handled: Composition ______________________________
Temperature ____________ Specific gravity ____________
Average flow __________ Retention time @ 100% full ______

Design Data: Capacity ______________________ Pressure ______________
Horizontal or vertical ________ Diam. ________ Length ________
Type of end, top, or bottom closures ______________________________
____
Material of construction ______________________________

Agitation: Type ____________________ Diam. ______________
Speed ____________________ Brake Hp ______________
Connected Hp/unit __________ Motor ______________
Material of construction ______________________________

Heat Provision: Type (Jacket)(Coil)(Tube bundle)( )
Location ______________________________________
Size ____________ Material of construction ______________

Utilities:
Controls:
Insulation:
Tolerances:
Comments and Drawings:

FIG. 13-2. Specification sheet for storage tanks.

BUBBLE-CAP COLUMN

Identification: Item ______________ Date ____________
Item No. ____________
No. required __________ By ____________

Function:

Operation:

Materials Handled:	*Feed*	*Overhead*	*Reflux*	*Bottoms*
Quantity	________	________	________	________
Composition	________	________	________	________
Temperature	________	________	________	________

Design Data: No. of trays ____________________ Reflux ratio __________
Pressure ____________________ Tray spacing __________
Functional height ____________________ Skirt height __________
Material of construction ______________________________
Diameter: Liquid density ____________ lb/cu ft
Vapor density ____________ lb/cu ft
Maximum allowable vapor velocity (superficial) ____________ ft/sec
Maximum vapor flow rate ______________________ cu ft/sec
Recommended inside diameter ______________________________

Utilities:
Controls:
Insulation:
Tolerances:
Comments and Drawings:

FIG. 13-3. Specification sheet for bubble-cap distillation column.

PUMP

Identification: Item ________ Date ________
Item No. ________
No. required ________ By ________

Function:

Operation:

Materials Handled: Composition ________
Quantity ________
Temperature ________ Specific gravity ________
Viscosity ________
Vapor pressure ________

Design Data: Type of pump ________
Total discharge head ________ Net suction head ________
Differential head ________ Brake Hp ________
Material of construction ________
Type of drive ________ Type of motor ________
Connected Hp/unit ________

Utilities:
Controls:
Insulation:
Tolerances:
Comments:

FIG. 13-4. Specification sheet for pumps.

Scaling Up in Design

When accurate data are not available in the literature or when past experience does not give an adequate design basis, pilot-plant tests may be necessary in order to design effective plant equipment. The results of these tests must be scaled up to the plant capacity. A design engineer, therefore, should be acquainted with the limitations of scale-up methods, and he should know how to select the essential design variables.

Pilot-plant data are almost always required for the design of filters unless specific information is already available for the type of materials and conditions involved. Heat exchangers, distillation columns, pumps, and many other types of conventional equipment can usually be designed adequately without using pilot-plant data.

Table 1 presents an analysis of important factors in the design of different types of equipment.* This table shows the major variables that characterize the size or capacity of the equipment and the maximum scale-up ratios for these variables. Information on the need for pilot-plant data, safety factors, and essential operational data for the design are included in Table 1.

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* M. Laurent, R. D. Beattie, and T. H. Goodgame, *Chem. Eng. Progr.*, 50:332 (1954).

Table 1. Factors in Equipment Scale-up and Design

Type of equipment	Is pilot plant usually necessary?	Major variables for operational design (other than flow rate)	Major variables characterizing size or capacity	Maximum scale-up ratio based on indicated characterizing variable	Approximate recommended safety or overdesign factor, %
Centrifugal pumps	No	Discharge head	Flow rate	>100:1	10
			Power input	>100:1	
			Impeller diameter	10:1	
Cooling towers	No	Air humidity	Flow rate	>100:1	15
		Temperature decrease	Volume	10:1	
Cyclones	No	Particle size	Flow rate	10:1	10
			Diameter of body	3:1	
Hammer mills	Yes	Size reduction	Flow rate	60:1	20
			Power input	60:1	
Packed columns	No	Equilibrium data	Flow rate	>100:1	15
		Superficial vapor velocity	Diameter	10:1	
			Height to diameter ratio		
Plate columns	No	Equilibrium data	Flow rate	>100:1	15
		Superficial vapor velocity	Diameter	10:1	
Plate-and-frame filters	Yes	Cake resistance or permeability	Flow rate	>100:1	20
			Filtration area	>100:1	
Reciprocating compressors	No	Compression ratio	Flow rate	>100:1	10
			Power input	>100:1	
			Piston displacement	>100:1	
Rotary filters	Yes	Cake resistance or permeability	Flow rate	>100:1	20
			Filtration area	25:1	
Screw conveyors	No	Bulk density	Flow rate	90:1	20
			Diameter	8:1	
			Drive horsepower		
Spray condensers	No	Latent heat of vaporization	Flow rate	70:1	20
			Height to diameter ratio	12:1	
		Temperatures			
Tube-and-shell heat exchanger	No	Temperatures	Flow rate	>100:1	15
		Viscosities	Heat-transfer area	>100:1	
		Thermal conductivities			

Safety Factors

Some examples of recommended safety factors for equipment design are shown in Table 1. These factors represent the amount of overdesign that could be used to account for changes in the operating performance with time.

The indiscriminate application of safety factors can be very detrimental to a design, and the engineer must resist the temptation to protect himself by excessive use of these factors. Each piece of equipment should be designed to carry out its necessary function. Then, if uncertainties are involved, a reasonable safety factor can be applied. The role of the particular piece of equipment in the over-all operation must be considered along with the consequences of underdesign. Fouling, which may occur during operation, should never be overlooked when a design safety factor is determined. Potential increases in capacity requirements are sometimes used as an excuse for applying large safety factors. This practice, however, can result in so much overdesign that the process or equipment never has an opportunity to prove its economic value.

In general design work, the magnitudes of safety factors are dictated by economic or market considerations, the accuracy of the design data and calculations, potential changes in the operating performance, background information available on the over-all process, and the amount of conservatism used in developing the individual components of the design. Each safety factor must be chosen on the basis of existing conditions, and the design engineer should not hesitate to use a safety factor of zero if he thinks it is correct.

MATERIALS OF CONSTRUCTION

The effects of corrosion and erosion must be considered in the design of chemical plants and equipment. Chemical resistance and physical properties of constructional materials, therefore, are important factors in the choice and design of equipment. The materials of construction must be resistant to the corrosive action of any chemicals that may contact the exposed surfaces. Possible erosion caused by flowing fluids or other types of moving substances must be considered, even though the materials of construction may have adequate chemical resistance. Structural strength, resistance to physical or thermal shock, cost, ease of fabrication, necessary maintenance, and general type of service required, including operating temperatures and pressures, are additional factors that influence the final choice of constructional materials.

If there is any doubt concerning suitable materials for the construction of equipment, reference should be made to the literature, or laboratory tests should be carried out under conditions similar to the final operating conditions. The results from laboratory tests indicate the corrosion resistance of the material and also the effects on the product caused by contact with the particular material. Further tests on a pilot-plant scale may be desirable in order to determine the amount of erosion resistance or the effects of other operational factors.

Metals

Materials of construction may be divided into the two general classifications of *metals* and *nonmetals*. Pure metals and metallic alloys are included under the first classification. Table 2 presents data showing the comparison of purchased cost for various types of metals in plate form.

TABLE 2. COMPARISON OF PURCHASED COST FOR METAL PLATE *

Material	Ratio $= \dfrac{\text{cost per pound for metal}}{\text{cost per pound for steel}}$
Flange quality steel †	1
304 stainless-steel-clad steel	5
316 stainless-steel-clad steel	6
Aluminum (99 plus)	6
304 stainless steel	7
Copper (99.9 plus)	7
Nickel-clad steel	8
Monel-clad steel	8
Inconel-clad steel	9
316 stainless steel	10
Monel	10
Nickel	12
Inconel	13
Hastelloy C	40

* J. Donavon, *Chem. Eng. Progr.*, **50**:320 (1954).

† Purchased cost for steel plate (January, 1957) can be approximated as 6 to 12 cents per pound, depending on the amount purchased.

Iron and Steel. Although many materials have greater corrosion resistance than iron and steel, cost aspects favor the use of iron and steel. As a result, they are often used as materials of construction when it is known that some corrosion will occur. If this is done, the presence of iron salts and discoloration in the product can be expected, and periodic replacement of the equipment should be anticipated.

In general, cast iron and carbon steel exhibit about the same corrosion resistance. They are not suitable for use with dilute acids, but they can be used with many strong acids, since a protective coating composed of corrosion products forms on the metal surface.

Because of the many types of rolled and forged steel products used in industry, basic specifications are needed to designate the various types. The American Iron and Steel Institute (AISI) has set up a series of standards for steel products.*† A few examples showing specifications and designations for iron and steel products are presented in Table 3.

TABLE 3. EXAMPLES OF SPECIFICATIONS AND DESIGNATIONS FOR IRON AND STEEL PRODUCTS

Gray cast iron contains approximately 3.5% carbon.

Structural carbon steel, in general, contains about 0.25% carbon and 0.5% manganese.

Austenitic cast iron of the common type contains 20% nickel or nickel and copper in the ratio of about 2.5:1.

Duriron has greater corrosion resistance to acids than ordinary cast iron because large amounts of silicon are included in the alloy. The approximate composition is 14.5% Si, 0.85% C, 0.65% Mn, and 84% Fe.

AISI number	Per cent chemical composition, limits for open-hearth and electric-furnace alloy steels *						
	C	Mn	P	S	Si	Ni	Cr
A 1330	0.28–0.33	1.60–1.90	0.040	0.040	0.20–0.35		
A 1340	0.38–0.43	1.60–1.90	0.040	0.040	0.20–0.35		
A 2330	0.28–0.33	0.60–0.80	0.040	0.040	0.20–0.35	3.25–3.75	
A 2340	0.38–0.43	0.70–0.90	0.040	0.040	0.20–0.35	3.25–3.75	
A 3130	0.28–0.33	0.60–0.80	0.040	0.040	0.20–0.35	1.10–1.40	0.55–0.75
A 3140	0.38–0.43	0.70–0.90	0.040	0.040	0.20–0.35	1.10–1.40	0.55–0.75

* Molybdenum and vanadium contents are listed for some alloys. For a detailed listing, see J. H. Perry, "Chemical Engineers' Handbook," 3d ed., McGraw-Hill Book Company, Inc., New York, 1950.

Stainless Steels. There are more than 30 standard types of stainless steels. These materials are high chromium or high nickel-chromium alloys of iron containing small amounts of other essential constituents. They have excellent corrosion-resistance and heat-resistance properties. The most common stainless steels, such as type 302 or type 304, contain approximately 18 per cent chromium and 8 per cent nickel, and they are designated as 18-8 stainless steels.

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* American Iron and Steel Institute, Manufacturers' Standard Practice, July 1, 1946.

† Specifications and codes on materials have also been established by the Society of Automotive Engineers (SAE), the American Society of Mechanical Engineers (ASME), and the American Society for Testing Materials (ASTM). In the AISI and SAE numbering systems, the first digit indicates the type of steel: 1 for carbon steel, 2 for nickel steel, 3 for nickel-chromium steel, 4 for molybdenum steel, 5 for chromium steel, 6 for chromium-vanadium steel, 7 for tungsten steel, and 9 for silicon-manganese steel. The last two digits give the approximate percentage of carbon as hundredths of 1 per cent. For simple alloys, the second digit usually represents the approximate percentage of the predominant alloying element.

The addition of molybdenum to the alloy, as in type 316, increases the corrosion resistance and high-temperature strength. If nickel is not included, the low-temperature brittleness of the material is increased and the ductility and pit-type corrosion resistance are reduced. The presence of chromium in the alloy gives resistance to oxidizing agents. Thus, type 430, which contains chromium but no nickel or molybdenum, exhibits excellent corrosion resistance to nitric acid and other oxidizing agents.

Although fabricating operations on stainless steels are more difficult than on standard carbon steels, all types of stainless steel can be fabricated successfully.* The properties of types 430F, 416, 410, 310, 309, and 303 make these materials particularly well suited for machining or other fabricating operations. In general, machinability is improved if small quantities of phosphorus, selenium, or sulfur are present in the alloy.

The types of stainless steel included in the 300 series are hardenable only by cold-working; those included in the 400 series are either nonhardenable or hardenable by heat-treating. As an example, type 410, containing 12 per cent chromium and no nickel, can be heat-treated for hardening and has good mechanical properties when heat-treated. It is often used as a material of construction for bubble caps, turbine blades, or other items that require special fabrication.

Stainless steels exhibit the best resistance to corrosion when the surface is oxidized to a passive state. This condition can be obtained, at least temporarily, by a so-called "passivation" operation in which the surface is treated with nitric acid and then rinsed with water. Localized corrosion can occur at places where foreign material collects, such as in scratches, crevices, or corners. Consequently, mars or scratches should be avoided, and the equipment design should specify a minimum of sharp corners, seams, and joints.

The high temperatures involved in welding stainless steel may cause precipitation of chromium carbide at the grain boundary, resulting in decreased corrosion resistance along the weld. The chances of this occurring can be minimized by using low-carbon stainless steels or by controlled annealing.

Table 4 presents the compositions of standard types of stainless steel. Some typical applications of the various types are shown in Table 5.

Hastelloy. The beneficial effects of nickel, chromium, and molybdenum are combined in Hastelloy C to give an expensive but highly corrosion-resistant material. A typical analysis of this alloy shows 56 per cent nickel, 17 per cent molybdenum, 16 per cent chromium, 5 per cent iron, and 4 per

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* For a detailed discussion of machining and fabrication of stainless steels, see "Stainless Steel Handbook," and "The Fabrication of Stainless Steels," Allegheny Ludlum Steel Corporation, Pittsburgh, Pa., 1956.

TABLE 4. COMPOSITION OF STANDARD STAINLESS STEELS *†

AISI type number ‡	Composition, per cent					
	C	Mn max	Si max	Cr	Ni	Other
301	Over 0.08–0.15	2.00	1.00	16.0–18.0	6.0–8.0	
302	Over 0.08–0.15	2.00	1.00	17.0–19.0	8.0–10.0	
302B	Over 0.08–0.20	2.00	2.0–3.0	17.0–19.0	8.0–10.0	
303	0.15 max	2.00	1.00	17.0–19.0	8.0–10.0	§
304	0.08 max	2.00	1.00	18.0–20.0	8.0–11.0	
304L	0.03 max	2.00	1.00	18.0–20.0	8.0–11.0	
305	0.12 max	2.00	1.00	17.0–19.0	10.0–13.0	
308	0.08 max	2.00	1.00	19.0–21.0	10.0–12.0	
309	0.20 max	2.00	1.00	22.0–24.0	12.0–15.0	
309S	0.08 max	2.00	1.00	22.0–24.0	12.0–15.0	
310	0.25 max	2.00	1.50	24.0–26.0	19.0–22.0	
310S	0.08 max	2.00	1.50	24.0–26.0	19.0–22.0	
314	0.25 max	2.00	1.5–3.0	23.0–26.0	19.0–22.0	
316	0.10 max	2.00	1.00	16.0–18.0	10.0–14.0	Mo, 2.00–3.00
316L	0.03 max	2.00	1.00	16.0–18.0	10.0–14.0	Mo, 1.75–2.50
317	0.10 max	2.00	1.00	18.0–20.0	11.0–14.0	Mo, 3.00–4.00
321	0.08 max	2.00	1.00	17.0–19.0	8.0–11.0	Ti, 5 × C min
347	0.08 max	2.00	1.00	17.0–19.0	9.0–12.0	Cb, 10 × C min
403	0.15 max	1.00	0.50	11.5–13.0		
405	0.08 max	1.00	1.00	11.5–13.5	. . . .	Al, 0.10–0.30
410	0.15 max	1.00	1.00	11.5–13.5		
414	0.15 max	1.00	1.00	11.5–13.5	1.25–2.50	
416	0.15 max	1.25	1.00	12.0–14.0	. . . .	§
420	Over 0.15	1.00	1.00	12.0–14.0		
430	0.12 max	1.00	1.00	14.0–18.0		
430F	0.12 max	1.25	1.00	14.0–18.0	. . . .	§
431	0.20 max	1.00	1.00	15.0–17.0	1.25–2.50	
440A	0.60–0.75	1.00	1.00	16.0–18.0	. . . .	Mo, 0.75 max
440B	0.75–0.95	1.00	1.00	16.0–18.0	. . . .	Mo, 0.75 max
440C	0.95–1.20	1.00	1.00	16.0–18.0	. . . .	Mo, 0.75 max
446	0.35 max	1.50	1.00	23.0–27.0	1.00 max	N, 0.25 max
501	Over 0.10	1.00	1.00	4.0–6.0		
502	0.10 max	1.00	1.00	4.0–6.0		

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* Sixteenth Biennial Materials of Construction Report, *Chem. Eng.*, vol. 61, no. 11, 1954.

† "Stainless Steel Handbook," Allegheny Ludlum Steel Corporation, Pittsburgh, Pa., 1956.

‡ In general, stainless steels in the 300 series contain large amounts of chromium and nickel; those in the 400 series contain large amounts of chromium and little or no nickel; those in the 500 series contain low amounts of chromium and little or no nickel; in the 300 series, except for type 309, the nickel content can be 10 per cent or less if the second number is zero and greater than 10 per cent if the second number is one; in the 400 series, an increase in the number represented by the last two digits indicates an increase in the chromium content. (NOTE: This is not in agreement with the SAE and general AISI steel numbering systems, which use a first digit of four for molybdenum steels and a first digit of five for chromium steels, while the third and fourth digits represent the carbon content.)

§ Phosphorus or sulfur or selenium, 0.07 per cent min; zirconium or molybdenum, 0.60 per cent max.

TABLE 5. APPLICATIONS OF STAINLESS STEEL AS MATERIALS OF CONSTRUCTION

AISI type number	*Applications*
301	Chutes for abrasive solids, structural components
302	Heat exchangers, towers, tanks, pipes, heaters, general chemical equipment
303	Pumps, valves, instruments, fittings
304	Perforated blow-pit screens, heat-exchanger tubing, preheater tubes
305	Funnels, utensils, hoods
308	Welding rod, more ductile welds for type 430
309	Welding rod for type 304, heat exchangers, pump parts
310	Jacketed high-temperature–high-pressure reactors, oil-refining-still tubes
314	Radiant tubes, carburizing boxes, annealing boxes
316	Distillation equipment for producing fatty acids, sulfite paper processing equipment, used for resistance to severe pit-type corrosion
317	Process equipment involving strong acids or chlorinated solvents
321	Furnace parts in presence of corrosive fumes
347	Like 302 but used where carbide precipitation during fabrication or service may be harmful, welding rod for type 321
403	Steam turbine blades
405	Tower linings, baffles, separator towers
410	Bubble-tower parts for petroleum refining, pump rods and valves, turbine blades
416	Valve stems, plugs, gates
420	High-spring-temper applications, utensils
430	Nitric acid storage tanks, furnace parts, fan scrolls
430F	Pump shafts, instrument parts, valve parts
431	Products requiring high yield point and resistance to shock
440A, B, C	Cutting edges, shear blades
446	Boiler baffles, furnace linings, glass molds

cent tungsten, with manganese, silicon, carbon, phosphorus, and sulfur making up the balance. Hastelloy C is used where structural strength and good corrosion resistance are necessary under conditions of high temperatures. The material can be machined and is readily fabricated. It is used in the form of valves, piping, heat exchangers, and various types of vessels. Other types of Hastelloys are also available for use under special corrosive conditions.

Copper and Its Alloys. Copper is relatively inexpensive, possesses fair mechanical strength, and can be fabricated easily into a wide variety of shapes. Although it shows little tendency to dissolve in nonoxidizing acids, it is readily susceptible to oxidation. Copper is resistant to atmospheric moisture or oxygen because a protective coating composed primarily of copper oxide is formed on the surface. The oxide, however, is soluble in most acids, and copper is not a suitable material of construction when it must contact any acid in the presence of oxygen or oxidizing agents. Copper exhibits good corrosion resistance to strong alkalies, with the exception of ammonium hydroxide. At room temperature it can handle sodium and potassium hydroxide of all concentrations. It resists most organic solvents and aqueous solutions of organic acids.

Copper alloys, such as brass, bronze, admiralty, and Muntz metals, can exhibit better corrosion resistance and better mechanical properties than pure copper. In general, high-zinc alloys should not be used with acids or alkalies owing to the possibility of dezincification. Most of the low-zinc alloys are resistant to hot dilute alkalies.

Nickel and Its Alloys. Nickel exhibits high corrosion resistance to most alkalies. Nickel-clad steel is used extensively for equipment in the production of caustic soda and alkalies. The strength and hardness of nickel is almost as great as that of carbon steel, and the metal can be fabricated easily. In general, oxidizing conditions promote the corrosion of nickel, and reducing conditions retard it.

Monel, an alloy of nickel containing 67 per cent nickel and 30 per cent copper, is often used in the food industries. This alloy is stronger than nickel and has better corrosion-resistance properties than either copper or nickel. Another important nickel alloy is Inconel (77 per cent nickel and 15 per cent chromium). The presence of chromium in this alloy increases its resistance to oxidizing conditions.

Aluminum. The lightness and relative ease of fabrication of aluminum and its alloys are factors favoring the use of these materials. Aluminum resists attack by acids because a surface film of inert hydrated aluminum oxide is formed. This film adheres to the surface and offers good protection unless materials which can remove the oxide, such as halogen acids or alkalies, are present.

Lead. Pure lead has low creep and fatigue resistance, but its physical properties can be improved by the addition of small amounts of silver, copper, antimony, or tellurium. Lead-clad equipment is in common use in many chemical plants. The excellent corrosion-resistance properties of lead are caused by the formation of protective surface coatings. If the coating is one of the highly insoluble lead salts, such as sulfate, carbonate, or phosphate, good corrosion resistance is obtained. Little protection is offered, however, if the coating is a soluble salt, such as nitrate, acetate, or chloride. As a result, lead shows good resistance to sulfuric acid and phosphoric acid, but it is susceptible to attack by acetic acid and nitric acid.

Tantalum. The physical properties of tantalum are similar to those of mild steel, with the exception that its melting point (2996°C) is much higher. It is ordinarily used in the pure form, and it is readily fabricated into many different shapes. The corrosion-resistance properties of tantalum resemble those of glass. The metal is attacked by hydrofluoric acid, by hot concentrated alkalies, and by materials containing free sulfur trioxide. It is resistant to all other acids and is often used for equipment involving contact with hydrochloric acid.

Silver. Because of its low mechanical strength and high cost, silver is generally used only in the form of linings. Silver is resistant to alkalies and many hot organic acids. It also shows fair resistance to aqueous solutions of the halogen acids.

Galvanic Action between Two Dissimilar Metals. When two dissimilar metals are used in the construction of equipment containing a conducting fluid in contact with both metals, an electric potential may be set up between the two metals. The resulting galvanic action can cause one of the metals to dissolve into the conducting fluid and deposit on the other metal. As an example, if a piece of copper equipment containing a solution of sodium chloride in water is connected to an iron pipe, electrolysis can occur between the iron and copper, causing high rates of corrosion. As indicated in Table 6, iron is higher in the electromotive series than copper, and the iron pipe will gradually dissolve and deposit on the copper. The farther apart the two metals are in the electromotive series, the greater is the possible extent of corrosion due to electrolysis.

Nonmetals

Glass, cement, stoneware, brick, rubber, silica ware, and wood are common examples of nonmetals used as materials of construction. All of these materials have much lower thermal conductivities than metals, and special means of heating, such as injection of live steam or other forms of internal heating, are often necessary when nonmetals are used as the major constructional materials.

Many of the nonmetals have low structural strength. Consequently, they are often used in the form of linings or coatings bonded to metal supports. Glass-lined or rubber-lined equipment has many applications in the chemical industries. Glass-lined equipment is particularly useful because glass is resistant to almost all chemicals, major exceptions being hydrofluoric acid and strong alkalies.

Natural and synthetic rubbers are used as linings or as structural components for equipment in the chemical industries. By adding the proper ingredients, natural rubbers with varying degrees of hardness and chemical resistance can be produced. Hard rubbers are chemically saturated with sulfur. The vulcanized products are rigid and exhibit excellent resist-

TABLE 6. ELECTROMOTIVE SERIES OF METALS

List of metals arranged in decreasing order of their tendencies to pass into ionic form by losing electrons.

Metal	Ion	Standard electrode potential at 25°C
Lithium	Li^+	+2.96
Potassium	K^+	2.92
Calcium	Ca^{++}	2.87
Sodium	Na^+	2.71
Magnesium	Mg^{++}	2.40
Aluminum	Al^{3+}	1.70
Manganese	Mn^{++}	1.10
Zinc	Zn^{++}	0.76
Chromium	Cr^{++}	0.56
Gallium	Ga^{3+}	0.50
Iron	Fe^{++}	0.44
Cadmium	Cd^{++}	0.40
Cobalt	Co^{++}	0.28
Nickel	Ni^{++}	0.23
Tin	Sn^{++}	0.14
Lead	Pb^{++}	0.12
Iron	Fe^{3+}	0.045
Hydrogen	H^+	0.0000
Antimony	Sb^{3+}	−0.10
Bismuth	Bi^{3+}	−0.23
Arsenic	As^{3+}	−0.30
Copper	Cu^{++}	−0.34
Copper	Cu^+	−0.47
Silver	Ag^+	−0.80
Lead	Pb^{4+}	−0.80
Platinum	Pt^{4+}	−0.86
Gold	Au^{3+}	−1.36
Gold	Au^+	−1.50

ance to chemical attack by dilute sulfuric acid and dilute hydrochloric acid.

The most common synthetic rubber is GR-S rubber (buna S) prepared by the copolymerization of butadiene and styrene. This material has chemical and physical properties similar to those of natural rubber. Some typical nonmetals, along with their special physical and chemical properties, are listed in Table 7.

TABLE 7. NONMETALS AS MATERIALS OF CONSTRUCTION

Material	Important constituents	Properties
High-silica glass	SiO_2—96% and higher	Exhibits good thermal-shock resistance.
Lime glass	SiO_2—70 to 75%, Na_2O—12 to 18%, CaO—5 to 14%	Ordinary window glass.
Borosilicate glass (Pyrex)	SiO_2—73 to 82%, Na_2O—3 to 10%, B_2O_3—5 to 20%	Used for optical work, scientific work, pipe lines, and many other applications.
Lead glass	SiO_2—53 to 67%, Na_2O—5 to 10%, PbO—20 to 40%	Used for decorative and optical effects.
Carbon and graphite (Karbate)	Bonded with phenol formaldehyde or other acid-resistant resins	Not highly resistant to physical shock and not completely impervious to gases. Maximum temperature, 360°F. Maximum pressure, 80 psig. Used as pipe, fittings, valves, heat exchangers, tanks, etc.
Phenolic resins (Haveg)	Phenol formaldehyde resin or furane resin; asbestos or graphite filler may be included	Various types show excellent resistance to acids including halogen acids, alkalies, and many organic compounds. Maximum temperature, 270°F. Maximum pressure, 25 psig. Used as pipe, fittings, valves, tanks, etc.
Polyethylene	Polyethylene	Resistant to action of acids, alkalies, and many organic compounds. Used as tubing, pipes, valves, containers, gaskets, etc.
Vinyl chloride (Saran)	Vinyl chloride, vinylidene chloride copolymer	Resistant to most inorganic chemicals and most organic solvents. Major exceptions are ammonium hydroxide and aromatic ketones. Used as tubing, pipe, fittings, etc.
Vinyl chloride (Tygon)	Vinyl chloride resins, vinyl chloride copolymers, vinyl chloride–acetate resins	Depending on type of Tygon, resistant to most chemicals. Used as linings, sheets, tubing, etc.
Unplasticized polyvinyl chloride	No plasticizing agent or copolymer included	Rigid material with excellent resistance to acids and other chemicals. Used as valves, pipe, sheets, etc.
Acrylic resins (Lucite, Plexiglas)	Polymethyl methacrylate	Shows excellent chemical resistance to weak acids and alkalies. Resists aliphatic hydrocarbons. Available as rods, sheets, tubing, etc.
Fluorinated resins (Teflon)	Polytetrafluoroethylene	Attacked only by molten alkali metals and fluorine at high temperatures and pressures. Thermally stable from −100 to 500°F. Tends to flow under compression. Used as lining, gaskets, valve seats, and for electrical applications.

TABLE 8. CORROSION RESISTANCE OF CONSTRUCTIONAL MATERIALS *

Code designation for corrosion resistance

A = acceptable, can be used successfully
C = caution, resistance varies widely depending on conditions; used when some corrosion is permissible
X = unsuitable
Blank = information lacking

Code designation for gasket materials

a = asbestos, white (compressed or woven)
b = asbestos, blue (compressed or woven)
c = asbestos (compressed and rubber-bonded)
d = asbestos (woven and rubber-frictioned)
e = GR-S or natural rubber
f = Teflon

Chemical	Metals								Nonmetals					Acceptable nonmetallic gasket materials
	Iron and steel	Cast iron (Ni-resist)	Stainless steel		Nickel	Monel	Red brass	Aluminum	Industrial glass	Carbon (Karbate)	Phenolic resins (Haveg)	Acrylic resins (Lucite)	Vinylidene chloride (Saran)	
			18-8	18-8 Mo										
Acetic acid, crude.......	C	C	C	C	C	C	C	A	A	A	A	A	C	b, c, d, f
Acetic acid, pure..	X	X	C	A	C	A	X	A	A	A	A	X	X	b, c, d, f
Acetic anhydride.	C	C	A	A	A	A	X	A	A	A	A	X	C	b, c, d, f
Acetone	A	A	A	A	A	A	A	A	A	A	C	X	C	a, e, f
Aluminum chloride..	X	C	X	X	C	C	A	A	A	A	A	..	A	a, c, e, f
Aluminum sulfate...	X	C	C	A	C	C	X	A	A	A	A	A	A	a, c, d, e, f
Alums....	X	C	C	A	C	A	X	A	A	A	A	A	A	a, c, d, e, f
Ammonia (gas)	A	A	C	A	A	A	X	C	A	..	A	..	C	a, f
Ammonium chloride...	C	A	C	C	A	A	C	C	A	A	A	A	A	b, c, d, e, f
Ammonium hydroxide...	A	A	A	A	C	C	X	C	A	..	A	A	C	a, c, d, f
Ammonium phosphate (monobasic).	X	C	A	A	..	C	X	X	A	A	A	..		b, c, d, e, f
Ammonium phosphate (dibasic)	C	A	A	A	..	A	C	C	A	A	A	..		a, c, d, e, f
Ammonium phosphate (tribasic)	A	A	A	A	A	A	X	C	A	A	A	..	..	a, c, d, e, f
Ammonium sulfate..	C	A	C	C	A	A	C	A	A	A	A	A	A	b, c, d, e, f
Aniline	A	A	A	A		A	X	..	A	A	C	..	C	a, f

Benzene, benzol	A	A	A	A	A	A	A	A	A	A	A		C	a, f
Boric acid	X	C	A	A	A	A	C	A	A	A	A		A	a, c, d, e, f
Bromine	X	C	C	C	C	C	C		A	C	X		X	b, f
Calcium chloride	C	A	C	C	A	A	C	C	A	A	A	A	A	b, c, d, e, f
Calcium hydroxide	A	A	A	A		A	C							a, c, d, e, f
Calcium hypochlorite	X	C	C	A	C	C	C	C	A	A	C		C	b, c, d, f
Carbon tetrachloride	C	C	C	A	A	A	C	C	A	A	A	A	C	a, f
Carbonic acid	C	C	A	A	A	A	C	A	A	A	A	A	A	a, e, f
Chloracetic acid	X		X	X	C	C	X	C	A		A			b, f
Chlorine, dry	A	A	C	A	A	A	A	A	A	A	A		X	b, e, f
Chlorine, wet	X	X	X	X	X	X	X	X	A	C	A		X	b, e, f
Chromic acid	C	C	C	C	C	C	X	C	A	X	X	X	A	b, f
Citric acid	X	C	C	A	C	A	C	A	A	A	A	A	A	b, c, d, e, f
Copper sulfate	X	C	A	A	C	C	X	X	A	A	A	X		b, c, d, e, f
Ethanol	A	A	A	A	A	A	A	A	A	A	A		A	a, c, e, f
Ethylene glycol	A	A	A	A	A	A	A	A	A	A	A	A	C	a, c, e, f
Fatty acids	C	C	A	A	A	A	C	A	A	A	A		A	a, e, f
Ferric chloride	X	X	X	C	X	X	X	X	A	C	A		A	b, e, f
Ferric sulfate	X	X	C	A	C	C	X	C	A	C	A		A	b, c, e, f
Ferrous sulfate	C	A	A	A	A	A	C	C	A	A	A		C	
Formaldehyde	C	C	A	A	A	A	C	A	A	A	A		A	a, c, e, f
Formic acid	X		C	C	C	C	X	X	A	A	A		A	b, c, e, f
Glycerol	A	A		A	A	A	A	A	A	A	C	A	C	a, c, e, f
Hydrocarbons (aliphatic)	A	A	A	A	A	A	A	A	A	A	A	A	C	a, c, d, f
Hydrochloric acid	X	X	X	X	C	C	X	X	A	A	A	A	C	b, c, d, f
Hydrofluoric acid	C	X	X	X	C	C	X	X	X	A	C		C	b, f
Hydrogen peroxide	C		C	C	C	C	C	A	A	A	A	A	C	a, e, f
Lactic acid	X	C	C	A	C	C	A	C	A	A	A			a, b, c, d, e, f
Magnesium chloride	C	C	C	C	A	A	C	C	A	A	A		A	b, c, e, f
Magnesium sulfate	A	A	A	A	A	A	A	A	A		A		A	b, c, e, f
Methanol	A	A	A	A	A	A	A	A	A	A	A		A	a, c, e, f
Nitric acid	X	C	C	C	X	X	X	C	A	C	C		C	b, f
Oleic acid	C	C	A	A	A	A	C	A	A	A	A		A	a, e, f
Oxalic acid	C	C	C	C	C	A	C	C	A	A	A			b, c, d, e, f
Phenol (carbolic acid)	C	A	C	A	A	A	C	A	A	A	C	A	C	a, f
Phosphoric acid	C	C	C	A	C	C	X	X	C	A	A		A	b, c, f
Potassium hydroxide	C	C	A	A	A	A	X	X					C	a, e, f
Sodium bisulfate	X	C	A	A	A	A	C	C	A	A	A		A	b, c, d, e, f
Sodium carbonate	A	A	A	A	A	A	C	C	C	A	A	X		a, c, d, e, f

Table 8. Corrosion Resistance of Constructional Materials * (*Continued*)

Chemical	Metals								Nonmetals					Acceptable nonmetallic gasket materials
	Iron and steel	Cast iron (Ni-resist)	Stainless steel		Nickel	Monel	Red brass	Alu-mi-num	Indus-trial glass	Carbon (Kar-bate)	Phe-nolic resins (Ha-veg)	Acrylic resins (Lucite)	Vinyl-idene chlo-ride (Saran)	
			18-8	18-8 Mo										
Sodium chloride	A	A	C	C	A	A	C	C	A	A	A	..	..	a, c, d, e, f
Sodium hydroxide	A	A	A	A	A	A	C	X	C	A	A	A	C	a, c, d, f
Sodium hypochlorite	X	C	C	A	C	C	C	X	A	C	X	..	A	b, c, d, f
Sodium nitrate	A	A	A	A	A	A	C	A	A	A	A	..	..	b, c, d, e, f
Sodium sulfate	A	A	A	C	A	A	A	A	A	A	A	..	A	a, c, d, e, f
Sodium sulfide	A	A	C	A	A	A	X	X	C	A	A	..	..	a, e, f
Sodium sulfite	A	A	A	A	A	A	C	C	A	A	A			
Sodium thiosulfate	C	..	A	A	A	A	C	C	A	A	A	..	A	a, c, d, e, f
Stearic acid	C	A	A	A	A	A	C	A	A	A	A	..	.	a, e, f
Sulfur	A	C	C	C	C	C	C	C	A	A	A	..	.	a, e, f
Sulfur dioxide	C	C	C	C	C	C	C	A	A	A	A	..	A	a, f
Sulfuric acid (98% to fuming)	A	C	X	C	X	X	X	C	A	X	X	X	C	b, f
Sulfuric acid (75–95%)	A	C	X	X	X	C	X	X	A	C	X	X	C	b, f
Sulfuric acid (10–75%)	X	C	X	X	C	C	X	X	A	A	C	C	A	b, f
Sulfuric acid (<10%)	X	C	X	C	C	C	C	C	A	A	C	A	A	a, b, c, e, f
Sulfurous acid	X	.	C	A	X	X	C	C	A	A	A	.	C	b, c, d, e, f
Trichloroethylene	C	A	C	A	A	A	C	C	A	A	A	..	C	a, f
Zinc chloride	C	C	C	X	A	A	X	C	..	..	A	A	.	b, c, d, e, f
Zinc sulfate	C	A	A	A	A	A	C	C	..	..	..	..	.	b, c, d, e, f

* From miscellaneous sources. (See footnote on page 251.)

Gasket Materials

Metallic and nonmetallic gaskets of many different forms and compositions are used in industrial equipment. The choice of a gasket material depends on the corrosive action of the chemicals that may contact the gasket, the location of the gasket, and the type of gasket construction. Other factors of importance are the cost of the materials, pressure and temperature involved, and frequency of opening the joint.

Tabulated Data for Selecting Materials of Construction

Table 8 presents information on the corrosion resistance of common metals, nonmetals, and gasket materials. This table can be used as an aid in choosing materials of construction, but no single table can take into account all the factors that can affect corrosion. Temperature level, concentration of the corrosive agent, presence of impurities, physical methods of operation, and slight alterations in the composition of the constructional material can affect the degree of corrosion resistance. The final selection of a material of construction, therefore, may require reference to manufacturers' bulletins and consultation with persons who are experts in the particular field of application.*

FABRICATION OF EQUIPMENT

Fabrication expenses account for a large fraction of the purchased cost for equipment. A design engineer, therefore, should be acquainted with the methods for fabricating equipment, and the problems involved in the fabrication should be considered when equipment specifications are prepared.

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* The following are recommended references for information on materials of construction in the chemical industries:

1. Biennial reports on materials of construction published by *Chemical Engineering* in November of even-numbered years.

2. *Ind. Eng. Chem.*, vol. 39, October, 1947, and subsequent annual reviews on chemical engineering materials of construction.

3. J. H. Perry, "Chemical Engineers' Handbook," 3d ed., McGraw-Hill Book Company, Inc., New York, 1950.

4. H. H. Uhlig, "Corrosion Handbook," John Wiley & Sons, Inc., New York, 1948.

5. L. G. Vande Bogart, *Factory Management and Maintenance*, **103**(1):145 (1945).

6. J. A. Lee, "Materials of Construction for Chemical Process Industries," McGraw-Hill Book Company, Inc., New York, 1950.

7. H. H. Dunkle and E. C. Fetter, Chemical Resistance of Gasket Materials, *Chem. Eng.*, **53**(11):106 (1946).

8. W. Staniar, "Plant Engineering Handbook," McGraw-Hill Book Company, Inc., New York, 1950.

9. "Modern Plastics Encyclopedia Issue," published annually by Plastics Catalogue Corporation, Bristol, Conn.

Many of the design and fabrication details for equipment are governed by various codes, such as the ASME Codes. These codes can be used to indicate definite specifications or tolerance limits without including a large amount of descriptive restrictions. For example, fastening requirements can often be indicated satisfactorily by merely stating that all welding should be in accordance with the ASME Code.

The exact methods used for fabrication depend on the complexity and type of equipment being prepared. In general, however, the following steps are involved in the complete fabrication of major pieces of chemical equipment, such as tanks, autoclaves, reactors, towers, and heat exchangers:

1. Layout of materials
2. Cutting to correct dimensions
3. Forming into desired shape
4. Fastening
5. Testing
6. Heat-treating
7. Finishing

Layout. The first step in the fabrication is to establish the layout of the various components on the basis of detailed instructions prepared by the fabricator. Flat pieces of the metal or other constructional material involved are marked to indicate where cutting and forming are required. Allowances must be made for losses caused by cutting, shrinkage due to welding, or deformation caused by the various forming operations.

After the equipment starts to take shape, the location of various outlets and attachments will become necessary. Thus, the layout operation can continue throughout the entire fabrication. If tolerances are critical, an exact layout, with adequate allowances for deformation, shrinkage, and losses, is absolutely essential.

Cutting. Several methods can be used for cutting the laid-out materials to the correct size. *Shearing* is the cheapest method and is satisfactory for relatively thin sheets. The edge resulting from a shearing operation may not be usable for welding, and the sheared edges may require an additional grinding or machining treatment.

Burning is often used for cutting metals. This method can be employed to cut and, simultaneously, prepare a beveled edge suitable for welding. Carbon steel is easily cut by an oxyacetylene flame. The heat effects on the metal are less than those involved in welding. Stainless steels and nonferrous metals that do not oxidize readily can be cut by a method known as *powder* or *flux burning*. An oxyacetylene flame is used, and powdered iron is introduced into the cut to increase the amount of heat and improve the cutting characteristics. The high temperatures involved may affect the materials, resulting in the need for a final heat-treatment to restore corrosion resistance or removal of the heat-affected edges.

Sawing can be used to cut metals that are in the form of flat sheets. However, sawing is expensive, and it is used only when the heat effects from burning would be detrimental.

Forming. After the constructional materials have been cut, the next step is to form them into the desired shape. This can be accomplished by various methods, such as by rolling, bending, pressing, bumping (i.e., pounding), or spinning on a die. In some cases, heating may be necessary in order to carry out the forming operation. Because of work hardening of the material, annealing may be required before forming and between stages during the forming.

When the shaping operations are finished, the different parts are assembled and fitted for fastening. The fitting is accomplished by use of jacks, hoists, wedges, and other means. When the fitting is complete and all edges are correctly aligned, the main seams can be tack-welded in preparation for the final fastening.

Fastening. Riveting can be used for fastening operations, but electric welding is far more common and gives superior results. The quality of a weld is very important, because the ability of equipment to withstand pressure or corrosive conditions is often limited by the conditions along the welds. Although good welds may be stronger than the metal that is fastened together, design engineers usually assume a weld is not perfect and employ weld efficiencies of 80 to 95 per cent in the design of pressure vessels.

The most common type of welding is the *manual shielded-arc* process in which an electrode approximately 14 to 16 in. long is used and an electric arc is maintained manually between the electrode and the material being welded. The electrode melts and forms a filler metal, while, at the same time, the work material fuses together. A special coating is provided on the electrode. This coating supplies a flux to float out impurities from the molten metal and also serves to protect the metal from surrounding air until the metal has solidified and cooled below red heat. The type of electrode and coating is determined by the particular materials and conditions that are involved in the welding operation.

A *submerged-arc* process is commonly used for welding stainless steels and carbon steels when an automatic operation is acceptable. The electrode is a continuous roll of wire fed at an automatically controlled rate. The arc is submerged in a granulated flux which serves the same purpose as the coating on the rods in the shielded-arc process. The appearance and quality of the submerged-arc weld is better than that obtained by an ordinary shielded-arc manual process; however, the automatic process is limited in its applications to main seams or similar long-run operations.

Heliarc welding is used for stainless steels and most of the nonferrous materials. This process can be carried out manually, automatically, or semiautomatically. A stream of helium or argon gas is passed from a nozzle in the electrode holder onto the weld, where the inert gas acts as a shielding blanket to protect the molten metal. As in the shielded-arc and submerged-arc processes, a filler rod is fed into the weld, but the arc in the heliarc process is formed between a tungsten electrode and the base metal.

In some cases, fastening can be accomplished by use of various solders, such as brazing solder (mp, 1550 to 1660°F) containing about 50 per cent each of copper and zinc; silver solders (mp, 1200 to 1600°F) containing silver, copper, and zinc; or ordinary solder (mp, 430°F) containing 50 per cent each of tin and lead. Screw threads, packings, gaskets, and other mechanical methods are also used for fastening various parts of equipment.

Testing. All welded joints can be tested for concealed imperfections by X rays, and code specifications usually require X-ray examination of main seams. Hydrostatic tests can be conducted to locate leaks. Sometimes, delicate tests, such as a helium probe test, are used to check for very small leaks.

Heat-treating. After the preliminary testing and necessary repairs are completed, it may be necessary to heat-treat the equipment to remove forming and welding stresses, restore corrosion-resistance properties to heat-affected materials, and prevent stress-corrosion conditions. A low-temperature treatment may be adequate, or the particular conditions may require a full anneal followed by a rapid quench.

Finishing. The finishing operation involves preparing the equipment for final shipment. Sandblasting, polishing, and painting may be necessary. Final pressure tests at $1\frac{1}{2}$ to 2 or more times the design pressure are conducted together with other tests as demanded by the specified code or requested by the inspector.

PROBLEMS

1. A new plant requires a large rotary vacuum filter for the filtration of zinc sulfite from a slurry containing 1 lb of zinc sulfite solid per 20 lb of liquid. The liquid contains water, sodium sulfite, and sodium bisulfite. The filter must handle 8000 lb of slurry per hour. What additional information is necessary to design the rotary vacuum filter? How much of this information could be obtained from laboratory or pilot-plant tests? Outline the method for converting the test results to the conditions applicable in the final design.

2. For each of the following materials of construction, prepare an approximate plot of temperature versus concentration in water for sulfuric acid and for nitric acid, showing conditions of generally acceptable corrosion resistance:

(*a*) Stainless steel type 302.
(*b*) Stainless steel type 316.
(*c*) Karbate.
(*d*) Haveg.

3. A manhole plate for a reactor is to be 2 in. thick and 18 in. in diameter. It has been proposed that the entire plate be made of stainless steel type 316. The plate will have 18 bolt holes, and part of the face will need to be machined for close gasket contact. If the base price for stainless steel type 316 in the form of industrial plates is $0.70 per pound, estimate the purchased cost for the manhole plate.

4. In the course of developing a new product, a pilot plant is to be constructed for processing a new chemical compound. This new compound has been prepared only in laboratory glassware up to the present time. Outline the procedure that should be followed to make the best selection of materials of construction for the pilot plant.

5. Six tanks of different constructional materials and six different materials to be stored in these tanks are listed in the following columns:

Tanks	*Materials*
Brass-lined	20% hydrochloric acid
Carbon steel	10% caustic soda
Concrete	75% phosphoric acid for food products
Nickel-lined	98% sulfuric acid
Stainless steel type 316	Vinegar
Wood	Water

All tanks must be used, and all materials must be stored without using more than one tank for any one material. Indicate the material that should be stored in each tank.

6. For the design of internal-pressure cylindrical vessels, the API-ASME Code for Unfired Pressure Vessels (3d ed., pp. 13 and 14, 1938) recommends the following equations for determining the minimum wall thickness when extreme operating pressures are not involved:

$$t = \frac{PD_m}{2SE} + C \qquad \text{applies when } \frac{D_o}{D_i} < 1.2 \tag{1}$$

or

$$t = \frac{D_i}{2}\left(\sqrt{\frac{SE + P}{SE - P}} - 1\right) + C \qquad \text{applies when } \frac{D_o}{D_i} > 1.2 \tag{2}$$

where t = wall thickness, in.

P = internal pressure, psig (this assumes atmospheric pressure surrounding the vessel)

D_m = mean diameter, in.

D_i = ID, in.

D_o = OD, in.

E = fractional efficiency of welded or other joints

C = allowances, in., for corrosion, threading, and machining

S = design stress, psi (for the purpose of this problem, S may be taken as one-fourth of the ultimate tensile strength)

A cylindrical storage tank is to have an ID of 12 ft and a length of 36 ft. The seams will be welded, and the material of construction will be plain carbon steel (0.15 per cent C). The maximum working pressure in the tank will be 100 psig, and the maximum temperature will be 80°F. No corrosion problems are anticipated. On the basis of the preceding equations, estimate the necessary wall thickness.

7. A proposal has been made to use stainless-steel tubing as part of the heat-transfer system in a nuclear reactor. High temperatures and extremely high rates of heat transfer will be involved. Under these conditions, temperature stresses across the tube walls will be high, and the design engineer must choose a safe wall thickness and tube diameter for the proposed unit. List in detail all information and data necessary to determine if a proposed tube diameter and gauge number would be satisfactory.*

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* See E. W. Luster, Fuel Steam Power, *Trans. ASME*, **53**(12):161 (1931), and D. M. Newitt, *Trans. Inst. Chem. Engrs. (London)*, **14**:85 (1936).

CHAPTER 14

MATERIALS HANDLING AND TRANSFER EQUIPMENT—DESIGN AND COSTS

The most common means for transferring materials is by pumps and pipes. Elevators, conveyors, fans, blowers, and similar kinds of equipment are also used extensively to handle and transfer various materials. The design engineer must decide which type of equipment is best suited for his purposes, and he must be able to prepare equipment specifications that will satisfy the operational demands of the process under reasonable cost conditions. Consequently, theoretical design principles, practical problems of operation, and cost considerations are all involved in the final choice of materials handling and transfer equipment.

PUMPS AND PIPING

Power Requirements

A major factor involved in the design of pumping and piping systems is the amount of power that is required for the particular operation. Mechanical power must be supplied by the pump to overcome frictional resistance, changes in elevation, changes in internal energy, and other resistances set up in the flow system.

The various forms of energy can be related by the total energy balance or the total mechanical-energy balance. On the basis of 1 lb of fluid flowing under steady conditions, the total energy balance may be written in differential form as

$$\frac{g}{g_c}\,dZ + d(pv) + \frac{V_i\,dV_i}{g_c} + du = \delta Q + \delta W \tag{1}$$

The total mechanical-energy balance in differential form is

$$\frac{g}{g_c}\,dZ + v\,dp + \frac{V_i\,dV_i}{g_c} = \delta W_o - \delta F \tag{2}$$

where g = local gravitational acceleration, usually taken as 32.17 ft/(sec)(sec)

g_c = conversion factor in Newton's law of motion, 32.17 ft-lb mass/(sec)(sec)(lb force)

Z = vertical distance above an arbitrarily chosen datum plane, ft

v = specific volume of the fluid, cu ft/lb mass

p = absolute pressure, lb force/sq ft

V_i = instantaneous or point linear velocity, fps

u = internal energy, ft-lb force/lb mass

Q = heat energy imparted as such to the fluid system from an outside source, ft-lb force/lb mass

W = shaft work, gross work input to the fluid system from an outside source, ft-lb force/lb mass

W_o = mechanical work imparted to the fluid system from an outside source,* ft-lb force/lb mass

F = mechanical-energy loss due to friction, ft-lb force/lb mass

Integration of these energy balances between "point 1" where the fluid enters the system and "point 2" where the fluid leaves the system gives

Total energy balance:

$$Z_1 \frac{g}{g_c} + p_1 v_1 + \frac{V_1^2}{2\alpha g_c} + u_1 + Q + W = Z_2 \frac{g}{g_c} + p_2 v_2 + \frac{V_2^2}{2\alpha g_c} + u_2 \qquad (3)$$

Total mechanical-energy balance:

$$Z_1 \frac{g}{g_c} - \int_1^2 v\,dp + \frac{V_1^2}{2\alpha g_c} + W_o = Z_2 \frac{g}{g_c} + \frac{V_2^2}{2\alpha g_c} + \Sigma F \qquad (4)$$

where V = average linear velocity, fps, and α = alpha, correction coefficient to account for use of average velocity, usually taken as 1.0 if flow is turbulent and 0.5 if flow is viscous. Equations (1) through (4) are sufficiently general for treatment of almost any flow problem, and they are the basis for many design equations that apply for particular simplified conditions.

Evaluation of the term $\int_1^2 v\,dp$ in Eq. (4) may be difficult if a compressible fluid is flowing through the system, because the exact path of the compression or expansion is often unknown. For noncompressible fluids, however, the specific volume v remains essentially constant and the integral term reduces simply to $v(p_2 - p_1)$. Consequently, the total mechanical-energy balance is especially useful and easy to apply when the flowing fluid can be considered as noncompressible.

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* The mechanical work W_o is equal to the total shaft work W minus the amount of energy transmitted to the fluid as a result of pump friction or pump inefficiency. When W_o is used in the total mechanical-energy balance, pump friction is not included in the term for the mechanical-energy loss due to friction F.

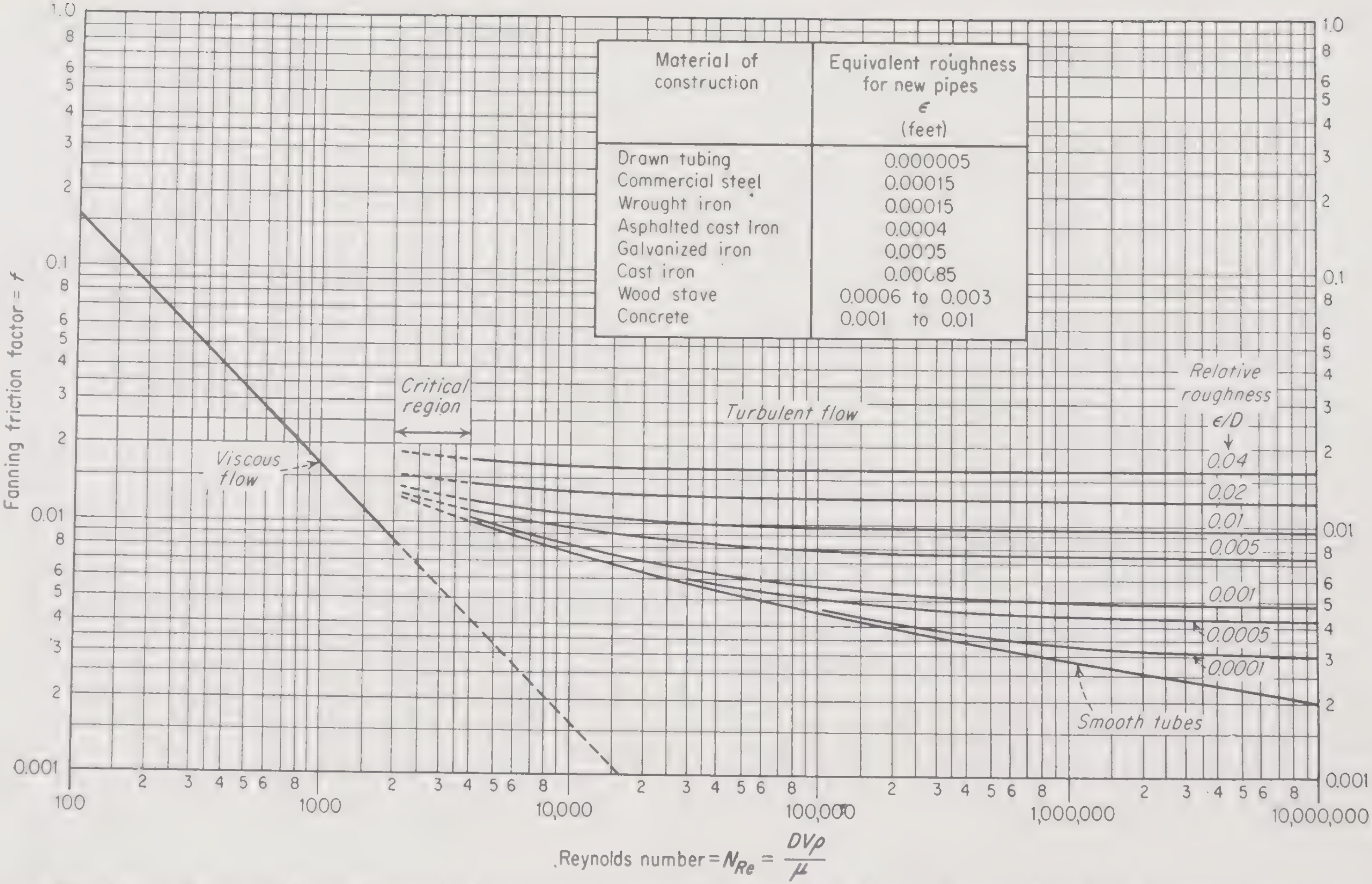
Friction. Frictional effects are extremely important in flow processes. In many cases, friction may be the main cause for resistance to the flow of a fluid through a given system. Consider the common example of water passing through a pipe. If no frictional effects were present, pipes of very small diameters could be used for all flow rates. Under these conditions, the pumping-power costs for forcing 100,000 gal of water per hour through a $\frac{1}{8}$-in.-diameter pipe would be the same as the power costs for forcing water at the same mass rate through a pipe of equal length having a diameter of 2 ft. In any real flow process, however, frictional effects *are* present, and they must be taken into consideration.

When a fluid flows through a conduit, the amount of energy lost due to friction depends on the properties of the flowing fluid and the extent of the conduit system. For the case of steady flow through long straight pipes of uniform diameter, the variables that affect the amount of frictional losses are the velocity at which the fluid is flowing (V), the density of the fluid (ρ), the viscosity of the fluid (μ), the diameter of the pipe (D), the length of the pipe (L), and the equivalent roughness of the pipe (ϵ). By applying the method of dimensional analysis to these variables, the following expression, known as the *Fanning equation*, can be obtained for the frictional effects in the system:

$$dF = \frac{-dp_f}{\rho} = \frac{2\mathfrak{f}V^2\,dL}{g_cD} \tag{5}$$

The friction factor $\mathfrak{f}$ is based on experimental data and has been found to be a function of the Reynolds number and the relative roughness of the pipe (ϵ/D). Figure 14-1 presents a plot of the friction factor versus the Reynolds number in straight pipes. In the viscous-flow region, the friction factor is not affected by the relative roughness of the pipe; therefore, only one line is shown in Fig. 14-1 for Reynolds numbers up to about 2100. In the turbulent-flow region, the relative roughness of the pipe has a large effect on the friction factor. Curves with different parameters of the dimensionless ratio ϵ/D are presented in Fig. 14-1 for values of Reynolds numbers greater than 2100. A table on the plot indicates values of ϵ for various pipe-construction materials. As the methods for determining $\mathfrak{f}$ do not permit high accuracy (±10 per cent), the value of the friction factor should not be read to more than two significant figures, and Fig. 14-1 gives adequate accuracy for determining the numerical size of the friction factor.

The values for equivalent pipe roughness given in Fig. 14-1 are only approximations, even for new pipe, and the values may increase because of surface pitting and corrosion after the pipe is in service. The design



Material of construction	Equivalent roughness for new pipes ϵ (feet)
Drawn tubing	0.000005
Commercial steel	0.00015
Wrought iron	0.00015
Asphalted cast Iron	0.0004
Galvanized iron	0.0005
Cast iron	0.00085
Wood stave	0.0006 to 0.003
Concrete	0.001 to 0.01

FIG. 14-1. Fanning friction factors for long straight pipes. [*Based on L. F. Moody, Trans. ASME*, **66**:671–684 (1944).]

engineer, therefore, should recognize the inherent inaccuracies in estimating the effects of pipe roughness, and this matter should be taken into consideration when the final design is prepared.

Curves similar to Fig. 14-1 are sometimes presented in the literature with a different defining value of $\mathfrak{f}$. For example, mechanical engineers usually define the friction factor so that it is exactly four times the friction factor given in Eq. (5).

The Reynolds number range between 2100 and 4000 is commonly designated as the *critical region*. In this range, there is considerable doubt as to whether the flow is viscous or turbulent. For design purposes, the safest practice requires the assumption that turbulent flow exists at all Reynolds numbers greater than 2100.

A mathematical expression for the friction factor can be obtained from the equation for the straight line in the viscous-flow region of Fig. 14-1. Thus, at Reynolds numbers below 2100

$$\mathfrak{f} = \frac{16}{N_{\mathrm{Re}}} = \frac{16\mu}{DV\rho} \tag*{(6) *}$$

Approximate equations showing the relationship between the friction factor and the Reynolds number in the turbulent-flow region have been developed. Three of these equations follow:

For smooth pipe or tubes,

$$\mathfrak{f} = 1.4 \times 10^{-3} + 0.125(N_{\mathrm{Re}})^{0.32} \tag*{(7) †}$$

$$\mathfrak{f} = \frac{0.046}{(N_{\mathrm{Re}})^{0.2}} \tag*{(7a)}$$

For new iron or steel pipe,

$$\mathfrak{f} = \frac{0.04}{(N_{\mathrm{Re}})^{0.16}} \tag*{(8)}$$

Integrated Form of the Fanning Equation. If the linear velocity, density, and viscosity of the flowing fluid remain constant and the pipe diameter is uniform over a total pipe length L, Eq. (5) can be integrated to give the following result:

$$F = \frac{-\Delta p_f}{\rho} = \frac{2\mathfrak{f}V^2L}{g_cD} \tag*{(9)}$$

In a strict sense, Eq. (9) is limited to conditions in which the flowing fluid is noncompressible and the temperature of the fluid is constant. When dealing with compressible fluids, such as air, steam, or any gas, it is good engineering practice to use Eq. (9) only if the pressure drop over the system is less than 10 per cent of the initial pressure. If a change in the fluid temperature occurs, Eq. (9) should not be used in the form indicated unless the total change in the fluid viscosity is less than approximately 50 per cent based on the maximum viscosity.*† If Eq. (9) is used when pressure changes or temperature changes are involved, the best accuracy is obtained by using the linear velocity, density, and viscosity of the fluid as determined at the average temperature and pressure. Exact results for compressible fluids or nonisothermal flow can be obtained from the Fanning equation by integrating the differential expression, taking all changes into consideration.

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* Substitution of this expression for $\mathfrak{f}$ into Eq. (5) results in the well-known Hagen-Poiseuille law for viscous flow.

† T. B. Drew, E. C. Koo, and W. H. McAdams, *Trans. AIChE*, **28**:56 (1933).

For turbulent flow in a conduit of noncircular cross section, an equivalent diameter can be substituted for the circular-section diameter, and the equations for circular pipes can then be applied without introducing a large error. This equivalent diameter is defined as four times the hydraulic radius R_H, where the hydraulic radius is the ratio of the cross-sectional flow area to the wetted perimeter. When the flow is viscous, substitution of $4R_H$ for D does not give accurate results, and exact expressions relating frictional pressure drop and velocity can be obtained only for certain conduit shapes.

Frictional Effects Due to End Losses, Fittings, Orifices, and Other Installations. If the cross-sectional area of a pipe changes gradually to a new cross-sectional area, the disturbances to the flow pattern can be so small that the amount of mechanical energy lost as friction due to the change in cross section is negligible. If the change is sudden, however, an appreciable amount of mechanical energy can be lost as friction. Similarly, the presence of bends, fittings, valves, orifices, or other installations that disturb the flow pattern can cause frictional losses. All of these effects must be included in the friction term appearing in the total mechanical-energy balance. Recommended expressions for evaluating the important types of frictional losses are presented in Table 1.

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* Over-all effects of temperature on the friction factor are more important in the streamline-flow range where $\mathfrak{f}$ is directly proportional to the viscosity than in the turbulent-flow range where $\mathfrak{f}$ is approximately proportional to $\mu^{0.16}$.

† For heating or cooling of fluids, a temperature gradient must exist from the pipe wall across the flowing fluid. E. N. Sieder and G. E. Tate, *Ind. Eng. Chem.*, **28**:1429 (1936), have indicated a simplified design procedure for this case as follows: When temperature and viscosity changes must be taken into consideration, the friction factor for use in Eq. (9) should be taken as the isothermal friction factor (Fig. 14-1) based on the arithmetic-average temperature of the fluid divided by a correction factor ϕ, where $\phi = 1.1(\mu_a/\mu_w)^{0.25}$ when DG/μ_a is less than 2100 and $\phi = 1.02(\mu_a/\mu_w)^{0.14}$ when DG/μ_a is greater than 2100. [G = mass velocity, lb/(hr)(sq ft of cross-sectional area); μ_a = viscosity of fluid at average bulk temperature, lb/(sec)(ft); μ_w = viscosity of fluid at temperature of wall, lb/(sec)(ft).]

Table 1. Expressions for Evaluating Frictional Losses in the Flow of Fluids through Conduits

For noncircular, cross-sectional area and turbulent flow, replace D by $4R_H = 4$ (cross-sectional flow area/wetted perimeter).

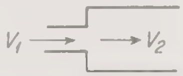
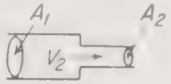
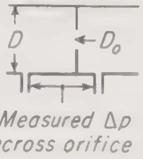
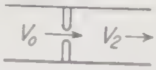
Friction caused by	General expression for frictional loss	Limited expression and remarks
Flow through long straight pipe of constant cross-sectional area	$dF = \frac{2\mathfrak{f}V^2\,dL}{g_cD}$	For case in which fluid is essentially noncompressible and temperature is constant $F = \frac{2\mathfrak{f}V^2L}{g_cD}$
Sudden enlargement	$F_e = \frac{(V_1 - V_2)^2}{2\alpha g_c}$	The following values for α may be used in design calculations: turbulent flow, $\alpha = 1$; streamline flow, $\alpha = 0.5$ 
Sudden contraction	$F_c = \frac{K_cV_2^2}{2\alpha g_c}$	The following values for α may be used in design calculations: turbulent flow, $\alpha = 1$; streamline flow, $\alpha = 0.5$  For $\frac{A_2}{A_1} < 0.715$, $K_c = 0.4\left(1.25 - \frac{A_2}{A_1}\right)$ For $\frac{A_2}{A_1} > 0.715$, $K_c = 0.75\left(1 - \frac{A_2}{A_1}\right)$ For conical or rounded shape, $K_c = 0.05$
Fittings, valves, etc.	$F = \frac{2\mathfrak{f}V^2L_e}{g_cD}$	L_e/D per fitting (dimensionless) 45° elbows .... 15 90° elbows, std. radius .... 32 90° elbows, medium radius .... 26 90° elbows, long sweep .... 20 90° square elbows .... 60 180° close-return bends 75

TABLE 1. EXPRESSIONS FOR EVALUATING FRICTIONAL LOSSES IN THE FLOW OF FLUIDS THROUGH CONDUITS (*Continued*)

Friction caused by	General expression for frictional loss	Limited expression and remarks	
Fittings, valves, etc.	$F = \frac{2fV^2L_e}{g_cD}$		L_e/D per fitting (dimensionless)
		180° medium-radius return bends . .	50
		Tee (used as elbow, entering run) . .	60
		Tee (used as elbow, entering branch)	90
		Couplings	Negligible
		Unions	Negligible
		Gate valves, open	7
		Globe valves, open	300
		Angle valves, open	170
		Water meters, disk	400
		Water meters, piston	600
		Water meters, impulse wheel	300
Sharp-edged orifice	$-\Delta p_f = F\rho$	$\frac{D_0}{D}$	$\frac{\Delta p_f(100)}{\Delta p \text{ across orifice}} = \%$
		0.8	40
		0.7	52
		0.6	63
		0.5	73
		0.4	81
		0.3	89
		0.2	95
			
Rounded orifice	$F = \frac{(V_0 - V_2)^2}{2\alpha g_c}$	The following values for α may be used in design calculations: turbulent flow, $\alpha = 1$; streamline flow, $\alpha = 0.5$	
			
Venturi	$-\Delta p_f = F\rho$	$-\Delta p_f$ = ⅛ to $\frac{1}{10}$ of total pressure drop from upstream section to venturi throat	

Design Calculations of Power Requirements. *Liquids.* For noncompressible fluids, the integrated form of the total mechanical-energy balance reduces to

$$W_o = \Delta Z + \Delta\left(\frac{V^2}{2\alpha g_c}\right) + \Delta(pv) + \Sigma F \tag{10}$$

where g is assumed to be numerically equal to g_c. Because the individual terms in Eq. (10) can be evaluated directly from the physical properties of the system and the flow conditions, the design engineer can apply this equation to many liquid-flow systems without making any major assumptions. The following example illustrates the application of Eq. (10) for a design calculation of the size of motor necessary to carry out a given pumping operation.

Example 1. Application of the Total Mechanical-energy Balance to Noncompressible-flow Systems. Water at 61°F is pumped from a large reservoir into the top of an overhead tank using standard 2-in.-diameter steel pipe (ID = 2.067 in.). The reservoir and the overhead tank are open to the atmosphere, and the difference in vertical elevation between the water surface in the reservoir and the discharge point at the top of the overhead tank is 70 ft. The length of the pipeline is 1000 ft. Two gate valves and three standard 90° elbows are included in the system. The efficiency of the pump is 40 per cent. This includes losses at the entrance and exit of the pump housing. If the flow rate of water is to be maintained at 50 gpm and the water temperature remains constant at 61°F, estimate the horsepower of the motor required to drive the pump.

Solution

BASIS: 1 lb of flowing water

Total mechanical-energy balance between point 1 (surface of water in reservoir) and point 2 (just outside of pipe at discharge point):

$$W_o = Z_2 - Z_1 + \frac{V_2^2}{2\alpha g_c} - \frac{V_1^2}{2\alpha g_c} + p_2v_2 - p_1v_1 + \Sigma F$$

Points 1 and 2 are taken where the linear velocity of the fluid is negligible; therefore

$$\frac{V_2^2}{2\alpha g_c} = 0 \qquad \text{and} \qquad \frac{V_1^2}{2\alpha g_c} = 0$$

$p_1 = p_2$ = atmospheric pressure. $v_1 = v_2$, since liquid water can be considered as a noncompressible fluid. $p_2v_2 - p_1v_1 = 0$. $Z_2 - Z_1 = 70$ ft-lb force/lb mass (assuming $g = g_c$).

Determination of friction:

Conversion factors:

$$7.48 \text{ gal} = 1 \text{ cu ft}$$

$$60 \text{ sec} = 1 \text{ min}$$

$$\text{Average velocity in 2-in. pipe} = \frac{(50)(144)}{(60)(7.48)(2.067)^2(0.785)} = 4.78 \text{ fps}$$

Viscosity of water at 61°F = 1.12 cp = (1.12)(0.000672) lb/(ft)(sec)

Density of water at 61°F = 62.3 lb/cu ft

$$\text{Reynolds number in 2-in. pipe} = \frac{(2.067)(4.78)(62.3)}{(12)(1.12)(0.000672)} = 68{,}000$$

$$\frac{\epsilon}{D} = \frac{(0.00015)(12)}{2.067} = 0.00087$$

$$\text{Friction factor} = \mathfrak{f} = 0.0057 \qquad \text{(from Fig. 14-1)}$$

$$\text{Total } L_e \text{ for fittings and valves} = \frac{(2)(7)(2.067)}{12} + \frac{(3)(32)(2.067)}{12}$$

$$= 19 \text{ ft}$$

Friction due to flow through pipe and all fittings

$$= \frac{2\mathfrak{f}V^2(L + L_e)}{g_cD}$$

$$= \frac{(2)(0.0057)(4.78)^2(1000 + 19)(12)}{(32.17)(2.067)}$$

$$= 47.9 \text{ ft-lb force/lb mass}$$

Friction due to contraction and enlargement (from Table 1)

$$= \frac{(0.5)(4.78)^2}{(2)(1)(32.17)} + \frac{(4.78 - 0)^2}{(2)(1)(32.17)}$$

$$= 0.53 \text{ ft-lb force/lb mass}$$

$$\Sigma F = 47.9 + 0.53 = 48.4 \text{ ft-lb force/lb mass}$$

From the total mechanical-energy balance, W_0 = theoretical mechanical energy necessary from pump = 70 + 48.4 = 118.4 ft-lb force/lb mass.

Conversion factor:

$$1 \text{ hp} = 550 \text{ ft-lb force/sec}$$

$$\text{hp of motor required to drive pump} = \frac{(118.4)(50)(62.3)}{(0.40)(60)(7.48)(550)} = 3.74 \text{ hp}$$

$$\frac{\text{ft-lb force}}{\text{lb mass}} \Big| \frac{\text{gal}}{\text{min}} \Big| \frac{\text{min}}{\text{sec}} \Big| \frac{\text{ft}^3}{\text{gal}} \Big| \frac{\text{lb mass}}{\text{ft}^3} \Big| \frac{\text{sec (hp)}}{\text{ft-lb force}} = \text{hp}$$

A 4.0-hp motor would be adequate for a design estimate.

Gases. Because of the difficulty that may be encountered in evaluating the exact integral of $v\,dp$ and dF for compressible fluids, use of the total mechanical-energy balance is not recommended for compressible fluids when large pressure drops are involved. Instead, the total energy balance should be used if the necessary data are available.

If g is assumed to be numerically equal to g_c, the integrated form of the total energy balance [Eq. (3)] can be written as

$$W = \Delta Z + \Delta h + \Delta\left(\frac{V^2}{2\alpha g_c}\right) - Q \tag{11}$$

where h = enthalpy = $u + pv$, ft-lb force/lb mass.

When Eq. (11) is applied in design calculations, information must be available for determining the change in enthalpy over the range of temperature and pressure involved. The following illustrative examples show how Eq. (11) can be used to calculate pumping power when compressible fluids are involved.

Example 2. Application of Total Energy Balance for the Flow of an Ideal Gas. Nitrogen is flowing under turbulent conditions at a constant mass rate through a long, straight, horizontal pipe. The pipe has a constant inside diameter of 2.067 in. At an upstream point (point 1), the temperature of the nitrogen is 70°F, the pressure is 15 psia, and the average linear velocity of the gas is 50 fps. At a given downstream point (point 2), the temperature of the gas is 140°F and the pressure is 50 psia. An external heater is located between points 1 and 2, and 10 Btu is transferred from the heater to each pound of the flowing gas. Except at the heater, no heat is transferred as such between the gas and the surroundings. Under these conditions, nitrogen may be considered to be an ideal gas, and the mean heat capacity C_p of the gas is 7.0 Btu/(lb mole)(°F). Estimate the total amount of energy (as foot-pounds force per pound of the flowing gas) supplied by the compressor located between points 1 and 2.

Solution

BASIS: 1 lb of flowing nitrogen

Total energy balance between points 1 and 2 for horizontal system and turbulent flow:

$$W = h_2 - h_1 + \frac{V_2^2}{2g_c} - \frac{V_1^2}{2g_c} - Q$$

where $V_1 = 50$ fps and $V_2 = (50)(600)(15)/(530)(50) = 17$ fps.

Conversion factor:

$$1 \text{ Btu} = 778 \text{ ft-lb force}$$

Since nitrogen can be considered as a perfect gas,

$$h_2 - h_1 = \frac{C_p}{M}(T_2 - T_1) = \frac{(7)(140 - 70)(778)}{28} = 13{,}600 \text{ ft-lb force/lb mass}$$

$$Q = (10)(778) \text{ ft-lb force/lb mass}$$

$$W = \text{total energy supplied by compressor}$$

$$= 13{,}600 + \frac{(17)^2}{(2)(32.17)} - \frac{(50)^2}{(2)(32.17)} - 7780$$

$$= 5790 \text{ ft-lb force/lb mass}$$

Example 3. Application of Total Energy Balance for the Flow of a Nonideal Gas (Steam Turbine). Superheated steam enters a turbine under such conditions that the enthalpy of the entering steam is 1340 Btu/lb. On the same basis, the enthalpy of the steam leaving the turbine is 990 Btu/lb. If the turbine operates under adiabatic conditions and changes in kinetic energy and elevation potential energy are negligible, estimate the maximum amount of energy obtainable from the turbine per pound of entering steam.

Solution

BASIS: 1 lb of entering steam

For an adiabatic system and negligible change in potential and kinetic energies, the total energy balance becomes

$$W = h_2 - h_1 = 990 - 1340 = -350 \text{ Btu/lb of steam}$$

Maximum energy obtainable from the turbine = 350 Btu/lb of steam.

When the data necessary for application of the total energy balance are not available, the engineer may be forced to use the total mechanical-energy balance for design calculations, even though compressible fluids and large pressure drops are involved. The following example illustrates the general method for applying the total mechanical-energy balance under these conditions.*

Example 4. Application of the Total Mechanical-energy Balance for the Flow of a Compressible Fluid with High Pressure Drop. Air is forced at a rate of 15 lb min through a straight, horizontal, steel pipe having an inside diameter of 2.067 in. The pipe is 3000 ft long, and the pump is located at the upstream end of the pipe. The air enters the pump through a 2.067-in.-ID pipe. The pressure in the pipe at the downstream end of the system is 5 psig, and the temperature is 70°F. If the air pressure in the pipe at the entrance to the pump is 10 psig and the temperature is 80°F, determine the following:

(*a*) The pressure in the pipe at the exit from the pump.

(*b*) The mechanical energy as foot-pounds force per minute added to the air by the pump, assuming the pump operation is isothermal.

Solution

BASIS: 1 lb mass of flowing air

Because the amount of heat exchanged between the surroundings and the system is unknown, the total energy balance cannot be used to solve this problem. However, an approximate result can be obtained from the total mechanical-energy balance.

Designate point 1 as the entrance to the pump, point 2 as the exit from the pump, and point 3 as the downstream end of the pipe. Under these conditions, the total mechanical-energy balance for the system between points 2 and 3 may be written as follows:

$$\int_2^3 v\,dp + \int_2^3 \frac{V\,dV}{\alpha g_c} = -\int_2^3 \delta F = -\int_2^3 \frac{2\mathfrak{f}V^2\,dL}{g_c D} \tag{A}$$

The mass velocity G [as lb mass/(sec)(sq ft)] is constant, and

$$V = Gv$$

$$dV = G\,dv$$

---

* For additional discussion and methods for integrating the total mechanical-energy balance when the flow of a compressible fluid and high pressure drop are involved, see J. H. Perry, "Chemical Engineers' Handbook," 3d ed., McGraw-Hill Book Company, Inc., New York, 1950; or J. M. Coulson and J. F. Richardson, "Chemical Engineering," vol. I, McGraw-Hill Book Company, Inc., New York, 1954.

Eliminating V and dV from Eq. (A) and dividing by v^2 gives

$$-\int_2^3 \frac{dp}{v} = \int_2^3 \frac{G^2\,dv}{\alpha g_c v} + \int_2^3 \frac{2\mathfrak{f}G^2\,dL}{g_c D} \qquad (B)$$

Assume that air acts as a perfect gas at the pressures involved, or

$$v = \frac{RT}{Mp} \qquad (C)$$

where M = molecular weight of air = 29 lb/lb mole
R = perfect-gas-law constant = 1545 (lb force/sq ft)(cu ft)/(lb mole)(°R)
T = temperature, °R

Substituting Eq. (C) into Eq. (B) and integrating gives

$$\frac{M}{2RT_{\text{avg}}}(p_2^2 - p_3^2) = \frac{G^2}{\alpha g_c} \ln \frac{v_3}{v_2} + \frac{2\mathfrak{f}_{\text{avg}} G^2 L}{g_c D} \qquad (D)$$

T_{avg} represents the average absolute temperature between points 2 and 3, and temperature variations up to 20 per cent from the average absolute value will introduce only a small error in the final result. The error introduced by using a constant $\mathfrak{f}_{\text{avg}}$ (based on average temperature and pressure) instead of the exact integrated value is not important unless pressure variations are considerably greater than those involved in this problem.

If the pump operation is isothermal, T_2 = 80°F and $T_{\text{avg}} = 75 + 460 = 535$°R. NOTE: If the pump operation were assumed to be adiabatic, a different value for T_{avg} would be obtained.

At 535°R,

$$\mu_{\text{air}} = 0.018 \text{ cp} = (0.018)(0.000672) \text{ lb/(sec)(ft)}$$

$$G = \frac{(15)(144)(4)}{(60)(2.067)^2(\pi)} = 10.77 \text{ lb/(sec)(sq ft)}$$

$$N_{\text{Re}} = \frac{DG}{\mu} = \frac{(2.067)(10.77)}{(12)(0.018)(0.000672)} = 153{,}000$$

$$\alpha = 1$$

$$\frac{\epsilon}{D} = \frac{(0.00015)(12)}{2.067} = 0.00087$$

From Fig. 14-1,

$$\mathfrak{f}_{\text{avg}} = 0.0052$$

$$p_3 = (5 + 14.7)(144) = 2840 \text{ lb force/sq ft}$$

Since air is assumed to act as a perfect gas,

$$\frac{v_3}{v_2} = \frac{T_3 p_2}{T_2 p_3} = \frac{(530)p_2}{(540)(2840)} = \frac{p_2}{2890}$$

Substituting into Eq. (D),

$$\frac{29}{(2)(1545)(535)}[p_2^2 - (2840)^2] = \frac{(10.77)^2}{32.17} \ln \frac{p_2}{2890} + \frac{(2)(0.0052)(10.77)^2(3000)(12)}{(32.17)(2.067)}$$

By trial-and-error solution,

(*a*)

$$p_2 = \text{pressure in pipe at exit from pump}$$

$$= 6750 \text{ psf} = {}^{6750}\!/_{144} \text{ psia} = 47 \text{ psia}$$

(*b*) The mechanical energy added by the pump can be determined by making a total mechanical-energy balance between points 1 and 3:

$$\int_1^3 v\,dp + \int_1^3 \frac{V\,dV}{\alpha g_c} = \int_1^3 \delta W_o - \int_1^3 \delta F \qquad (E)$$

The friction term, by definition, includes all friction except that occurring at the pump. Therefore,

$$\int_1^3 \delta F = \int_2^3 \delta F$$

and

$$\int_1^2 v\,dp + \int_2^3 v\,dp + \int_1^2 \frac{V\,dV}{\alpha g_c} + \int_2^3 \frac{V\,dV}{\alpha g_c} = W_o - \int_2^3 \delta F \qquad (F)$$

Subtracting Eq. (*A*) from Eq. (*F*) gives

$$\int_1^2 v\,dp + \int_1^2 \frac{V\,dV}{\alpha g_c} = W_o \qquad (G)$$

The value of $\int_1^2 v\,dp$ depends on the conditions or path followed in the pump, and the integral can be evaluated if the necessary *p-v* relationships are known. Although many pumps and compressors operate near adiabatic conditions, the pump operation will be assumed as isothermal in this example.

For a perfect gas and isothermal compression,

$$\int_1^2 v\,dp = \frac{RT}{M} \ln \frac{p_2}{p_1}$$

$$V_1 = Gv_1 = \frac{(10.77)(359)(540)(14.7)}{(29)(492)(24.7)} = 87 \text{ fps}$$

$$V_2 = V_1 \frac{p_1}{p_2} = \frac{(87)(24.7)}{47} = 46 \text{ fps}$$

$$W_o = \frac{RT}{M} \ln \frac{p_2}{p_1} + \frac{V_2^2}{2g_c} - \frac{V_1^2}{2g_c}$$

$$W_o = \frac{(1545)(540)}{29} \ln \frac{47}{24.7} + \frac{(46)^2}{(2)(32.17)} - \frac{(87)^2}{(2)(32.17)}$$

$$= 18{,}400 \text{ ft-lb force/lb mass}$$

Mechanical energy added to the air by the pump, assuming the pump operation is isothermal = (18,400)(15) = 276,000 ft-lb force/min.

The total power supplied to the pump could be determined if the isothermal efficiency of the pump (including any end effects caused by the pump housing) were known.

Piping Standards

Pipe Strength. Iron and steel pipes were originally classified on the basis of wall thickness as standard, extra-strong, and double-extra-strong. Modern industrial demands for more exact specifications have made these three classifications obsolete. Pipes are now specified according to wall thickness by a standard formula for *schedule number* as designated by the American Standards Association.

The bursting pressure of a thin-walled cylinder may be estimated from the following equation:

$$P_b = \frac{2S_T t_m}{D_m} \tag{12}$$

where P_b = bursting pressure (difference between internal and external pressures), psi

S_T = tensile strength, psi

t_m = minimum wall thickness, in.

D_m = mean diameter, in.

A safe working pressure P_s can be evaluated from Eq. (12) if the tensile strength is replaced by a safe working fiber stress S_s.

$$P_s = \frac{2S_s t_m}{D_m} \tag{13}$$

Schedule number is defined by the American Standards Association as the approximate value of

$$1000 \frac{P_s}{S_s} = \text{schedule number} \tag{14}$$

For temperatures up to 250°F, the recommended safe working stress is 9000 psi for lap-welded steel pipe and 6500 psi for butt-welded steel pipe.* If the schedule number is known, the safe working pressure can be estimated directly from Eq. (14).

Ten schedule numbers are in use at the present time. These are 10, 20, 30, 40, 60, 80, 100, 120, 140, and 160. For pipe diameters up to 10 in., schedule 40 corresponds to the former "standard" pipe and schedule 80 corresponds to the former "extra-strong" pipe. The original "double-extra-strong" pipe is not represented by a definite schedule number.

Nominal Pipe Diameter. Pipe sizes are based on the approximate diameter and are reported as nominal pipe sizes. Although the wall thickness varies depending on the schedule number, the outside diameter of any pipe having a given nominal size is constant and independent of the schedule number. This permits the use of standard fittings and threading tools on pipes of different schedule numbers. A table showing outside diameters, inside diameters, and other dimensions for pipes of different diameters and schedule numbers is presented in the Appendix.

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* For allowable stresses at other temperatures and for other materials of construction, see J. H. Perry, "Chemical Engineers' Handbook," 3d ed., p. 1650, McGraw-Hill Book Company, Inc., New York, 1950.

Tubing. Copper tubing and brass tubing are used extensively in industrial operations. Other metals, such as nickel and stainless steel, are also available in the form of tubing. Although pipe specifications are based on standard nominal sizes, tubing specifications are based on the actual outside diameter with a designated wall thickness. Conventional systems, such as the Birmingham wire gauge (BWG), are used to indicate the wall thickness. Common designations of tubing dimensions are given in the Appendix.

Fittings and Other Piping Auxiliaries. Threaded fittings, flanges, valves, flow meters, steam traps, and many other auxiliaries are used in piping systems to connect pieces of pipe together, change the direction of flow, regulate the flow, or obtain desired conditions in a flow system. Flanges are usually employed for piping connections when the pipe diameter is 3 in. or larger, while screwed fittings are commonly used for smaller sizes. In the case of cast-iron pipe used as underground water lines, bell-and-spigot joints are ordinarily employed rather than flanges.

The auxiliaries in piping systems must have sufficient structural strength to resist the pressure or other strains encountered in the operation, and the design engineer should provide a wide safety margin when specifying the ratings of these auxiliaries. Fittings, valves, steam traps, and similar items are often rated on the basis of the safe operating pressure as (*a*) low pressure (25 psi), (*b*) standard (125 psi), (*c*) extra-heavy (250 psi), or (*d*) hydraulic (300 to 10,000 psi). Figure 14-2 shows examples of standard designations used to indicate various types of fittings and auxiliaries in sketches of piping systems.

Design of Piping Systems *

The following items should be considered by the engineer when he is developing the design for a piping system:

1. Choice of materials and sizes
2. Effects of temperature level and temperature changes
    - *a.* Insulation
    - *b.* Thermal expansion
    - *c.* Freezing
3. Flexibility of the system for physical or thermal shocks

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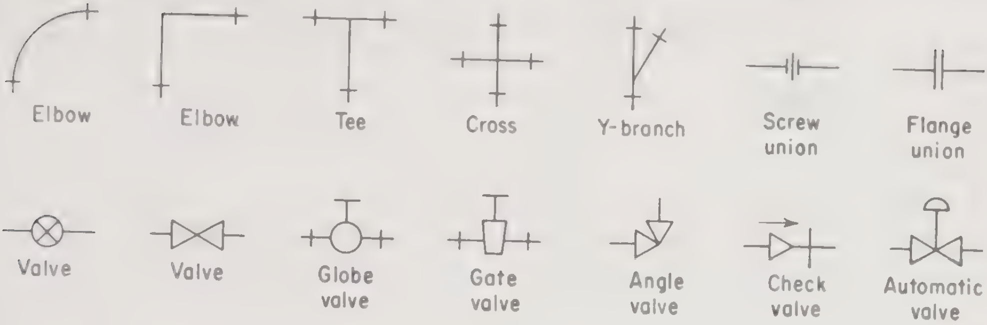
* For a detailed treatment of this subject, see M. W. Kellogg Co., "Design of Piping Systems," 2d ed., John Wiley & Sons, Inc., New York, 1956.



Color code for piping systems[a,b]

Fire protection	*Red*
Dangerous	*Yellow (low-pressure steam)* *Orange (high-pressure steam)* *Brown (gas)*
Safe	*Green, aluminum, white (air),* *black (electricity)*
Protective	*Blue (water)*
Radiation hazards (or extra valuable)	*Purple*

FIG. 14-2. Piping conventions for design drawings and piping systems. (*a*) (*Standard A-13, "Scheme for Identification of Piping Systems," ASME, American Standards Association, New York.*) (*b*) [*D. E. Garrett and W. A. Jordan, Chem. Eng.*, **63**(9):195 (1956).]

4. Adequate support and anchorage
5. Alterations in the system and the service
6. Maintenance and inspection
7. Ease of installation
8. Auxiliary or stand-by pumps and lines
9. Safety
    - *a*. Design factors
    - *b*. Relief valves and flare systems

In the early years of industrial development in the United States, many plants buried their outside pipelines. The initial cost for this type of installation is low because no supports are required and the earth provides insulation. However, location and repair of leaks are difficult, and other pipes buried in the same trench may make repairs impossible. Aboveground piping systems in industrial plants have proved to be more economical than buried systems, and, except for major water and gas lines, most in-plant piping systems in new plants are now located above ground or in crawl-space tunnels.

Thermal expansion and the resultant pipe stresses must be considered in any piping-system design. For example, if the temperature changes

TABLE 2. "RULE-OF-THUMB" ECONOMIC VELOCITIES FOR SIZING STEEL PIPELINES

Turbulent Flow

Type of fluid	Reasonable velocity, fps
Water or similar to water	3–10
Low-pressure steam (25 psig)	50–100
High-pressure steam (100 psig up)	100–200
Air at ordinary pressures (25–50 psig)	50–100

The preceding values apply for motor drives. Multiply indicated velocities by 0.6 to give reasonable velocities when steam turbine drives are used.

Viscous Flow (Liquids)

Nominal pipe diameter, in.	Reasonable velocity, fps		
	μ_c* = 50	μ_c = 100	μ_c = 1000
1	1.5–3	1–2	0.3–0.6
2	2.5–3.5	1.5–2.5	0.5–0.8
4	3.5–5.0	2.5–3.5	0.8–1.2
8	....	4.0–5.0	1.3–1.8

* μ_c = viscosity, centipoises.

from 50 to 600°F, the increase in length would be 4.9 in. per 100 ft for steel pipe and 7.3 in. per 100 ft for brass pipe. This amount of thermal expansion could easily cause a pipe or wall to buckle if the pipe were fastened firmly at each end with no allowances for expansion. The necessary flexibility for the piping system can be provided by the use of expansion loops, changes in direction, bellows joints, slip joints, and other devices.

The possibility of solidification of the fluid should not be overlooked in the design of a piping system. Insulation, steam tracing, and sloping the line to drain valves are methods for handling this type of problem.

Water hammer may cause extreme stresses at bends in pipelines. Consequently, liquid pockets should be avoided in steam lines through the use of steam traps and sloping of the line in the direction of flow. Quick-opening or quick-closing valves may cause damaging water hammer, and valves of this type may require protection by use of expansion or surge chambers.

A piping system should be designed so that maintenance and inspection can be accomplished easily, and the possibility of future changes in the system should not be overlooked. Personal-safety considerations in the design depend to a large extent on the fluids, pressures, and temperatures involved. For example, an overhead line containing a corrosive acid should be shielded from open walkways, and under no conditions should an unprotected flange in this type of piping system be located immediately over a walkway.

Pipe Sizing. The design engineer must specify the diameter of pipe that will be used in a given piping system, and economic factors must be considered in determining the optimum pipe diameter. Theoretically, the optimum pipe diameter is the one that gives the least total cost for annual pumping power and fixed charges with the particular piping system. Many short-cut methods have been proposed for estimating optimum pipe diameters, and some general "rules of thumb" for use in design estimates of pipe diameters are presented in Table 2.

The derivation of equations for determining optimum economic pipe diameters is presented in Chap. 9 (Optimum Design). The following simplified equations [Eqs. (45) and (47) in Chap. 9] can be used for making design estimates:

For turbulent flow ($N_{\mathrm{Re}} > 2100$) in steel pipes

$$D_{i,opt} = 3.9 q_f^{0.45} \rho^{0.13} \tag{15}$$

For viscous flow ($N_{\mathrm{Re}} < 2100$) in steel pipes

$$D_{i,opt} = 3.0 q_f^{0.36} \mu_c^{0.18} \tag{16}$$

where $D_{i,opt}$ = optimum inside pipe diameter, in.
q_f = fluid flow rate, cfs
ρ = fluid density, lb/cu ft
μ_c = fluid viscosity, centipoises

The preceding equations are the basis for the nomograph presented in Fig. 14-3, and this figure can be used for estimating the optimum diameter of steel pipe under ordinary plant conditions. Equations (15) and (16) should not be applied when the flowing fluid is steam, because the derivation makes no allowance for the effects of pressure drop on the value of the flowing material. Equation (15) is limited to conditions in which the viscosity of the fluid is between 0.02 and 20 centipoises.

Diameters estimated by Eqs. (15) and (16) or Fig. 14-3 are conservative in that they tend to be larger than the absolute optimum values. Consequently, the recommended design procedure is to choose the closest nominal diameter *below* the calculated value.

The constants in Eqs. (15) and (16) are based on average cost and operating conditions. When unusual conditions are involved or when a more accurate determination of the optimum diameter is desired, the following equations can be used:

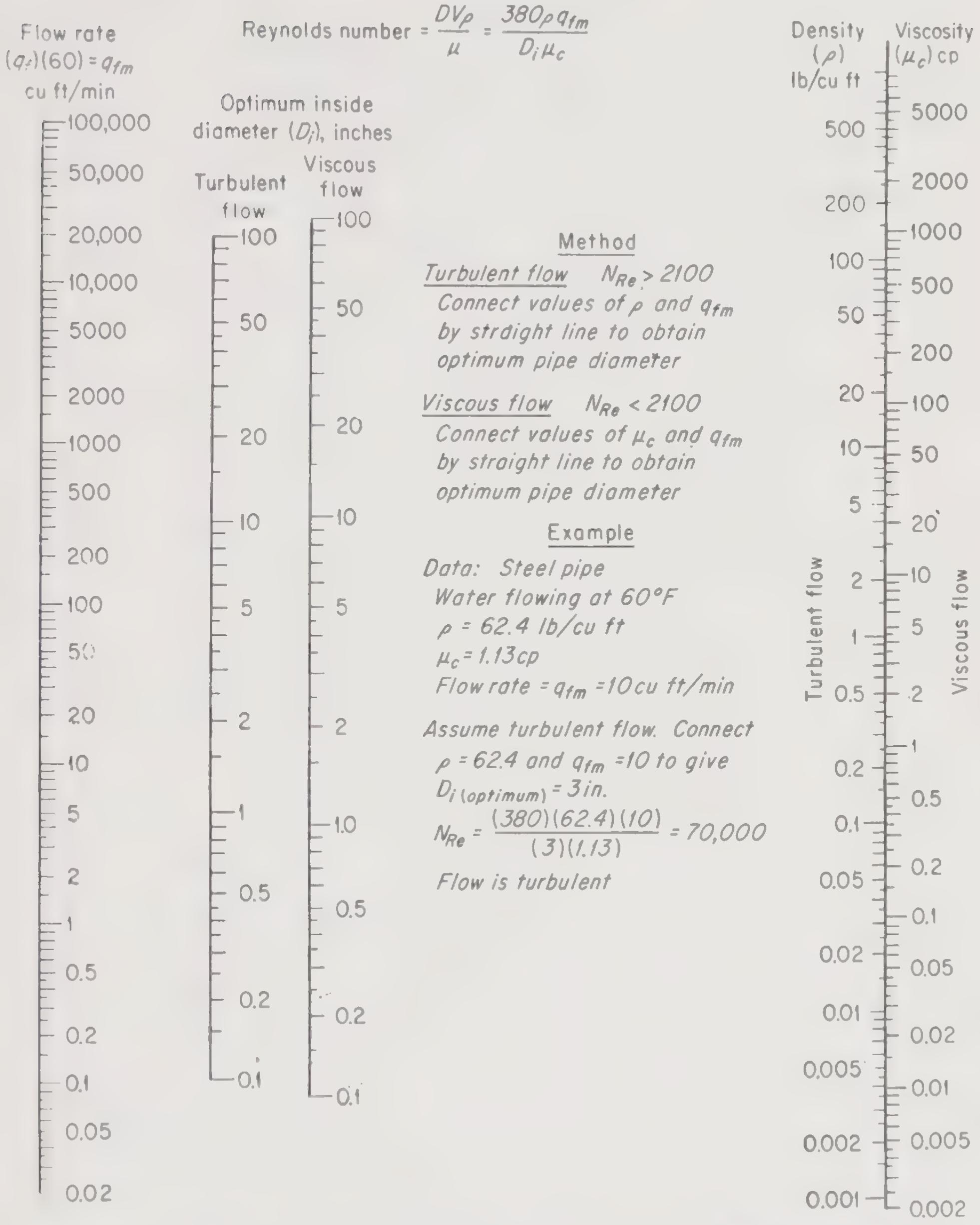
For turbulent flow

$$D_{i,opt} = \left[\frac{1.32 q_f^{2.84} \rho^{0.84} \mu_c^{0.16} K(1 + J)H_y}{n(1 + F_i)XEK_F}\right]^{1/(4.84+n)} \tag{17}$$

For viscous flow

$$D_{i,opt} = \left[\frac{0.096 q_f^{2} \mu_c K(1 + J)H_y}{n(1 + F_i)XEK_F}\right]^{1/(4.0+n)} \tag{18}$$

where K = cost of power, \$/kwhr
J = frictional loss due to fittings and bends, expressed as equivalent fractional loss in a straight pipe
H_y = hours of operation per year
X = purchase cost of new pipe per foot of pipe length if pipe diameter is 1 in., \$/ft
n = a constant with value dependent on type of pipe (purchase cost of new pipe per foot of pipe length = XD_i^n)
F_i = ratio of total costs for fittings and installation to purchase cost for new pipe; in an exact analysis, the cost for the pump and drive can also be included in F_i
E = efficiency of pump and drive, expressed as a fraction
K_F = annual fixed charges including maintenance, expressed as a fraction of the initial cost for the completely installed piping system



Reynolds number $= \frac{DV\rho}{\mu} = \frac{380\rho q_{fm}}{D_i \mu_c}$

Method

Turbulent flow $N_{Re} > 2100$
Connect values of ρ and q_{fm} by straight line to obtain optimum pipe diameter

Viscous flow $N_{Re} < 2100$
Connect values of μ_c and q_{fm} by straight line to obtain optimum pipe diameter

Example

Data: Steel pipe
Water flowing at 60°F
$\rho = 62.4$ *lb/cu ft*
$\mu_c = 1.13$ *cp*
Flow rate $= q_{fm} = 10$ *cu ft/min*

Assume turbulent flow. Connect $\rho = 62.4$ *and* $q_{fm} = 10$ *to give* $D_{i\,(optimum)} = 3$ *in.*

$$N_{Re} = \frac{(380)(62.4)(10)}{(3)(1.13)} = 70{,}000$$

Flow is turbulent

FIG. 14-3. Nomograph for estimation of optimum economic pipe diameters with turbulent or viscous flow. [*Based on B. R. Sarchet and A. P. Colburn, Ind. Eng. Chem.*, **32**:1249 (1940).]

Pipe Costs

Although accurate costs for pipes, valves, and piping-system auxiliaries can be obtained only by direct quotations from manufacturers, the design engineer can often make satisfactory estimates from data such as those presented in Figs. 14-4 through 14-10. The cost information presented in these figures covers the types of equipment most commonly encountered in industrial operations. For additional cost data on piping systems, the reader should refer to the tabulated "N-factor" results of Dickson,* manufacturers' bulletins, and the various books and articles giving detailed information on cost estimation.†‡

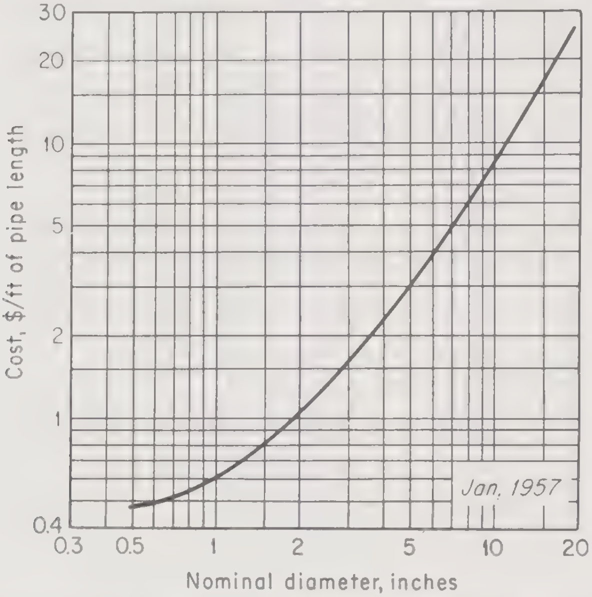


FIG. 14-4. Approximate cost for long-run steel piping, installed with necessary valves and fittings.

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* R. A. Dickson, Pipe Cost Estimation, *Chem. Eng.*, **57**(1):123 (1950).

† O. T. Zimmerman and I. Lavine, "Chemical Engineering Costs," 1950; "*Chemical Engineering Costs Quarterly*" and "Cost Engineering," Industrial Research Service, Dover, N.H.

‡ R. S. Aries and R. D. Newton, "Chemical Engineering Cost Estimation," McGraw-Hill Book Company, Inc., New York, 1955.

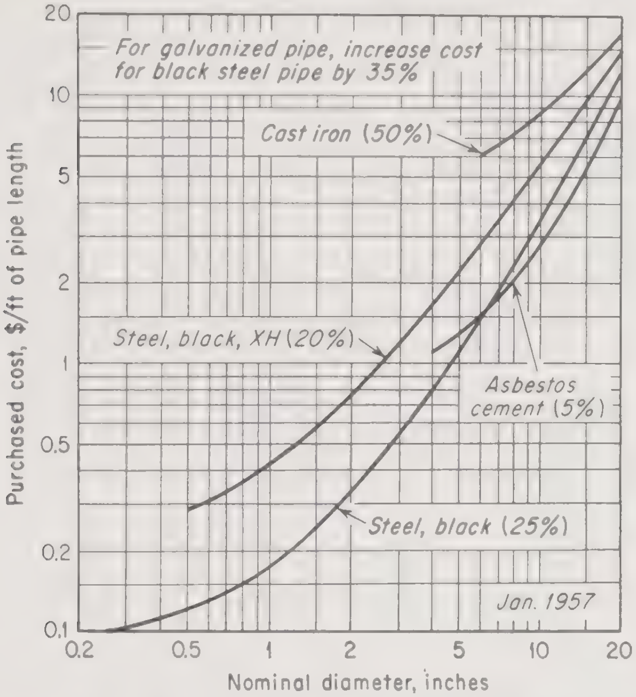

FIG. 14-5. Cost for pipe. Size is standard unless otherwise indicated. (Figures in parentheses indicate installation cost as per cent of material costs.)

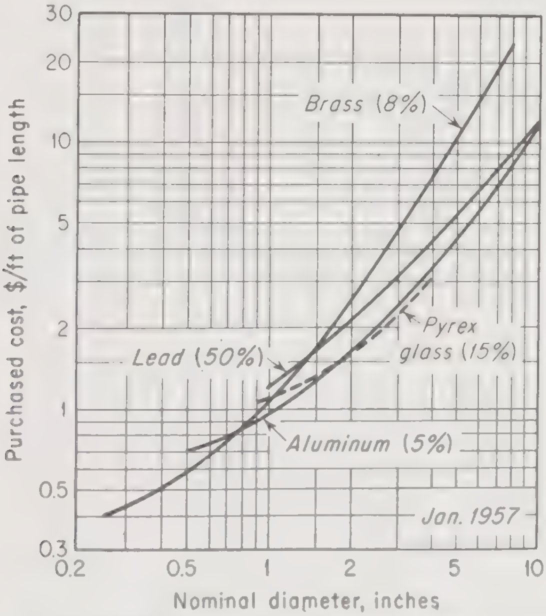

FIG. 14-6. Cost for standard pipe. (Figures in parentheses indicate installation cost as per cent of material costs.)

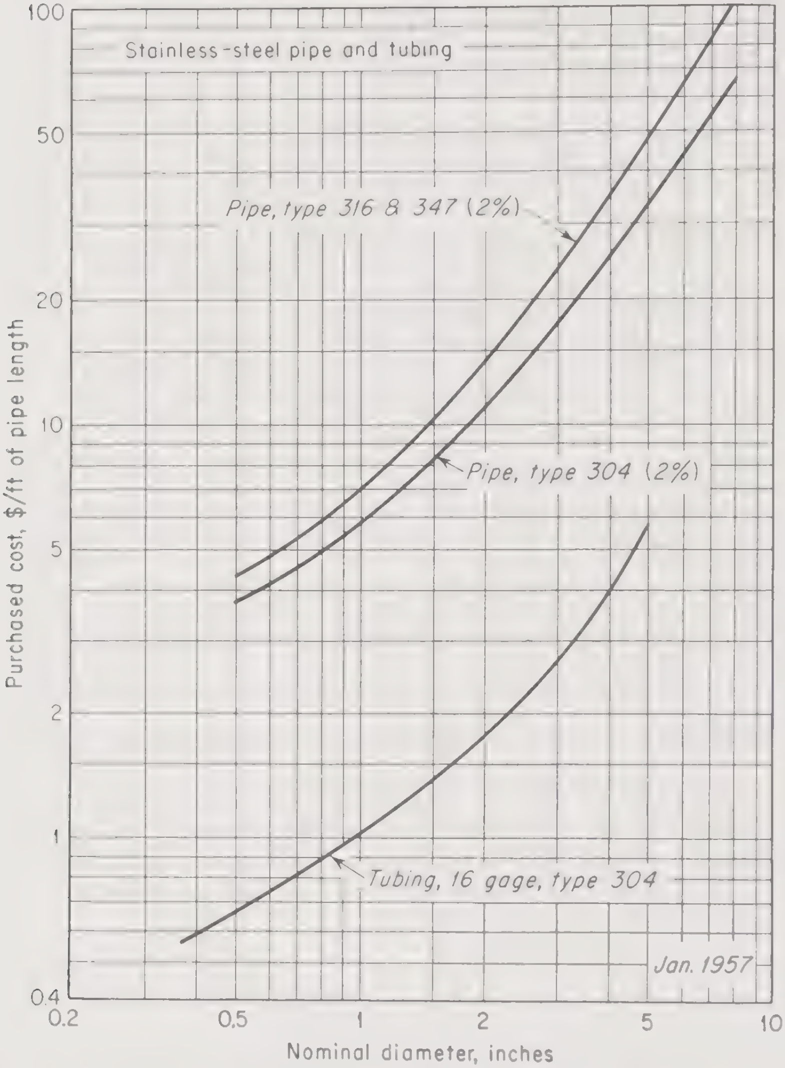

FIG. 14-7. Cost for standard stainless-steel pipe and tubing. (Figures in parentheses indicate installation cost as per cent of material costs.)

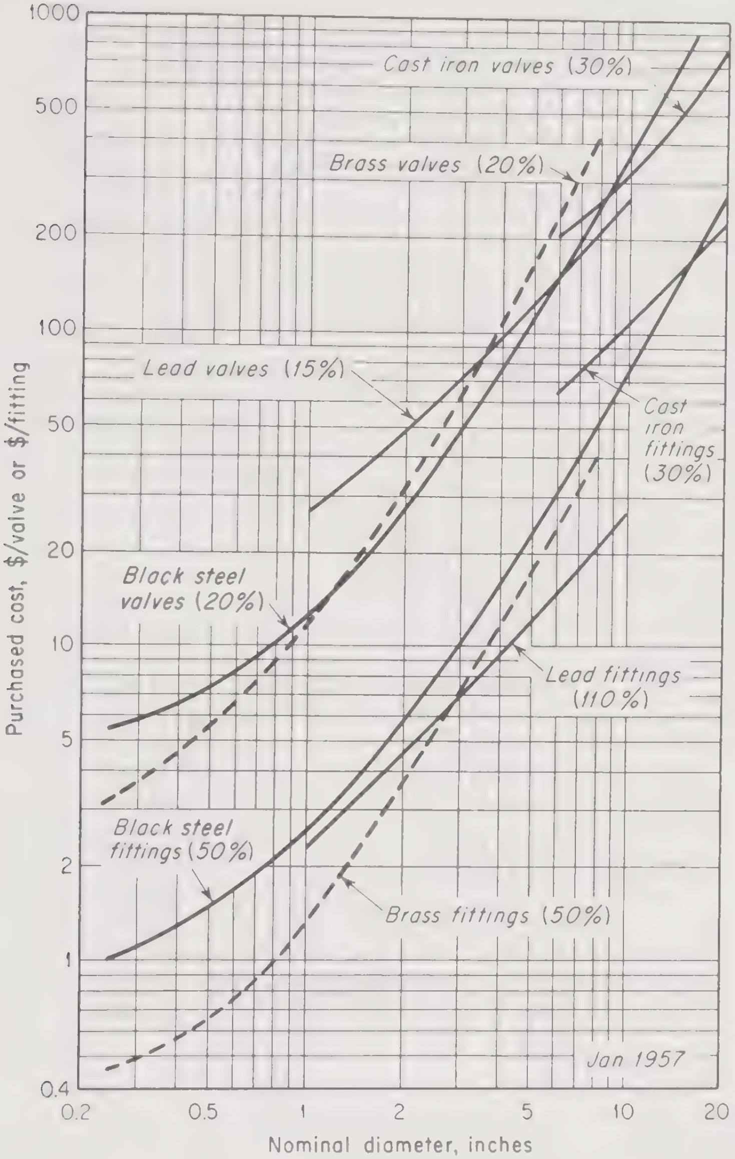

FIG. 14-8. Cost for standard fittings (tee) and standard valves (gate). (Figures in parentheses indicate installation cost as per cent of material costs.)

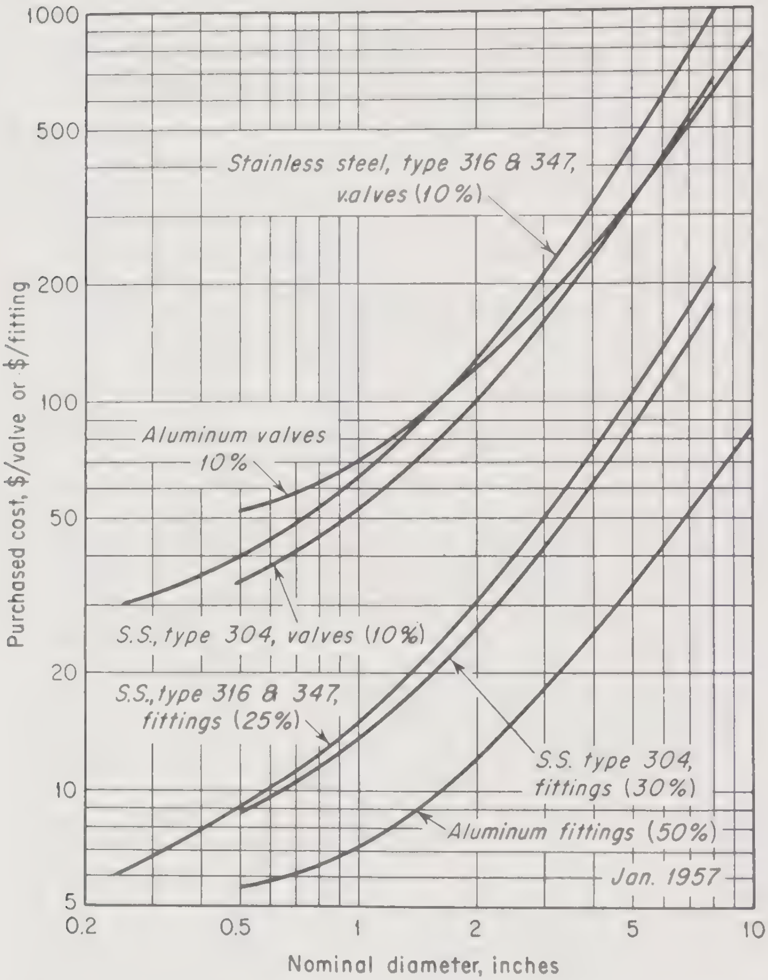

FIG. 14-9. Cost for standard fittings (tee) and standard valves (gate). (Figures in parentheses indicate installation cost as per cent of material costs.)

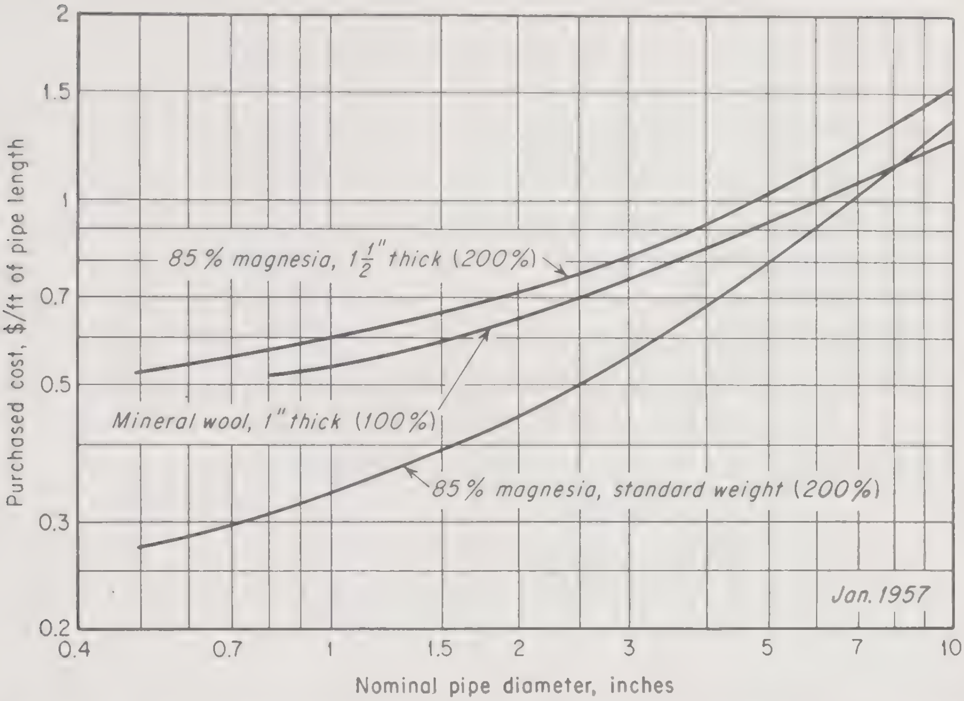

Fig. 14-10. Cost for pipe insulation. (Figures in parentheses indicate installation cost as per cent of material costs.)

Pumps

Pumps are used to transfer fluids from one location to another. The pump accomplishes this transfer by increasing the pressure of the fluid and, thereby, supplying the driving force necessary for flow. Power must be delivered to the pump from some outside source. Thus, electrical or steam energy may be transformed into mechanical energy which is used to drive the pump. Part of this mechanical energy is added to the fluid as work energy, and the rest is lost as friction due to inefficiency of the pump and drive.

Although the basic operating principles of gas pumps and liquid pumps are similar, the mechanical details are different because of the dissimilarity in physical properties of gases and liquids. In general, pumps used for transferring gases operate at higher speeds than those used for liquids, and smaller clearances between moving parts are necessary for gas pumps because of the lower viscosity of gases and the greater tendency for the occurrence of leaks.

The different types of pumps commonly employed in industrial operations can be classified as follows: *

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* For a detailed discussion on different types of pumps, see J. H. Perry, "Chemical Engineers' Handbook," 3d ed., McGraw-Hill Book Company, Inc., New York, 1950;

1. Reciprocating or positive-displacement pumps with valve action: piston pumps, diaphragm pumps, plunger pumps
2. Rotary positive-displacement pumps with no valve action: gear pumps, lobe pumps, screw pumps, eccentric-cam pumps, metering pumps
3. Rotary centrifugal pumps with no valve action: open impeller, closed impeller, volute pumps, turbine pumps
4. Air-displacement systems: air lifts, acid eggs or blow cases, jet pumps, barometric legs

Many different factors can influence the final choice of a pump for a particular operation. The following list indicates the major factors that govern pump selection:

1. The amount of fluid that must be pumped. This factor determines the size of pump (or pumps) necessary.
2. The properties of the fluid. The density and the viscosity of the fluid influence the power requirements for a given set of operating conditions; corrosive properties of the fluid determine the acceptable materials of construction. If solid particles are suspended in the fluid, this factor dictates the amount of clearance necessary and may eliminate the possibility of using certain types of pumps.
3. The increase in pressure of the fluid due to the work input of the pump. The head change across the pump is influenced by the inlet and downstream-reservoir pressures, the change in vertical height of the delivery line, and frictional effects. This factor is a major item in determining the power requirements.
4. Type of flow distribution. If nonpulsating flow is required, certain types of pumps, such as simplex reciprocating pumps, may be unsatisfactory. Similarly, if operation is intermittent, a self-priming pump may be desirable, and corrosion difficulties may be increased.
5. Type of power supply. Rotary positive-displacement pumps and centrifugal pumps are readily adaptable for use with electric-motor or internal-combustion-engine drives; reciprocating pumps can be used with steam or gas drives.
6. Cost and mechanical efficiency of the pump.

Reciprocating Pumps. A *reciprocating piston pump*, as illustrated in Figs. 14-11 and 14-12, delivers energy to a flowing fluid by means of a piston acting through a cylinder. Although steam is often employed as the source of power for this type of pump, the piston can be activated by other means, such as a rotating crankshaft operated by an electric motor. Thus, reciprocating piston pumps can be classified as *steam pumps* or *power*

G. G. Brown et al., "Unit Operations," John Wiley & Sons, Inc., New York, 1950. J. M. Coulson and J. F. Richardson, "Chemical Engineering," vol. 1, McGraw-Hill Book Company, Inc., New York, 1954; F. A. Kristal and F. A. Annett, "Pumps," 2d ed., McGraw-Hill Book Company, Inc., New York, 1953.

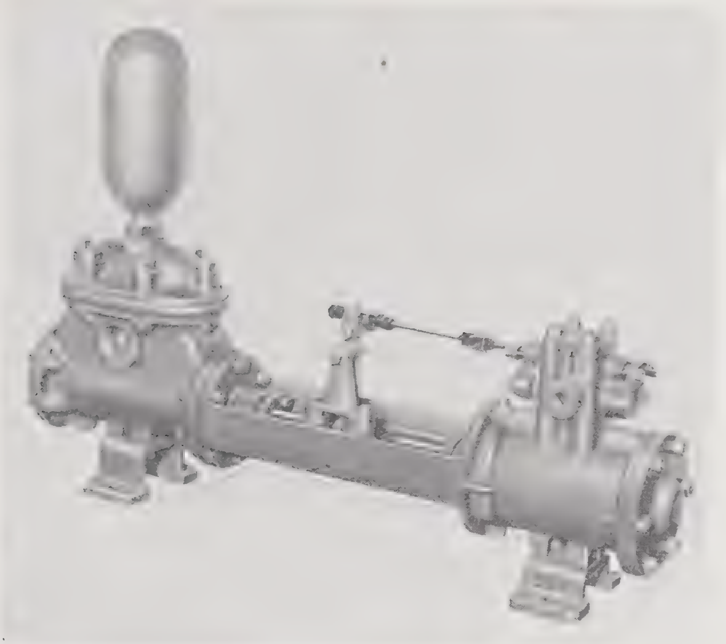

FIG. 14-11. Reciprocating, double-acting, simplex piston pump. (*Worthington Pump and Machinery Corporation.*)

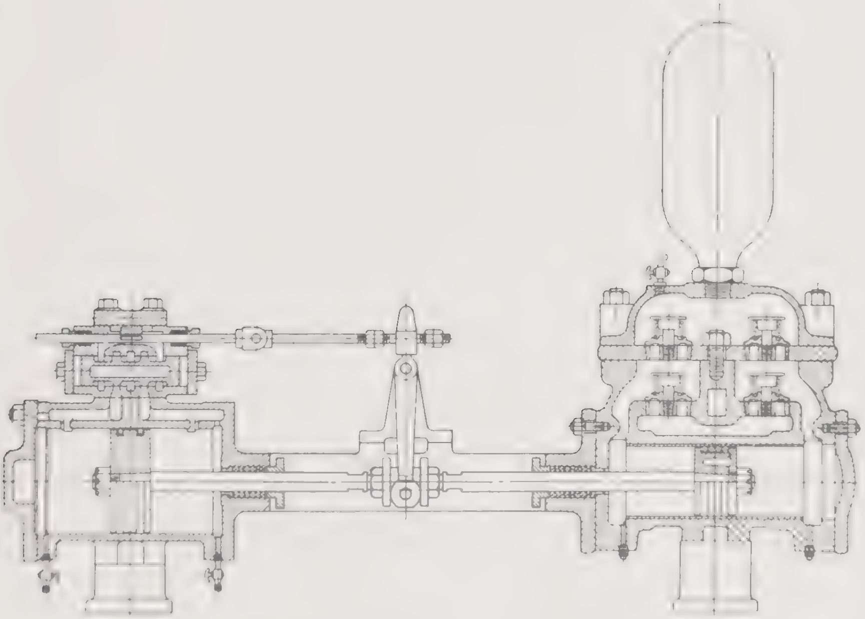

FIG. 14-12. Cutaway view of reciprocating, double-acting, simplex piston pump. (*Worthington Pump and Machinery Corporation.*)

pumps. They can also be classified as *single-acting* or *double-acting* depending on whether energy is delivered to the fluid on both the forward and backward strokes of the piston.

Specifications for reciprocating steam pumps are expressed in abbreviated form as diameter of the steam cylinder, diameter of the water cylinder, and length of the piston stroke in inches. For example, a 7 × 4½ × 12 pump has a steam-cylinder diameter of 7 in., a water-cylinder diameter of 4½ in., and a stroke length of 12 in. In general, reciprocating steam pumps having stroke lengths less than 10 in. should not operate at more than 100 strokes per minute because of excessive wear. For longer stroke lengths, reasonable piston speeds are in the range of 50 to 90 fpm.

In reciprocating steam pumps, the steam is not used expansively as in the common types of steam engines. Instead, essentially the full pressure of the steam is maintained throughout the entire stroke by keeping the steam-inlet ports fully open during the stroke. As the piston moves forward through the cylinder on the delivery side of the pump, the fluid is compressed and forced out of the cylinder. By a system of opening and closing valves, the piston can deliver energy to the fluid with every stroke.

The rate of fluid discharge from the cylinder is zero at the beginning of a piston stroke and increases to a maximum value when the piston reaches full speed. If only one discharge cylinder is used, the flow rate will pulsate as indicated in Fig. 14-13*a*. These pulsations can be reduced by placing an air chamber on the discharge line as shown in Fig. 14-12 or by using a number of delivery cylinders suitably compounded. *Simplex* pumps have only one delivery cylinder, *duplex* pumps have two cylinders, and *triplex* pumps have three cylinders. As indicated in Fig. 14-13*b*, the rate of discharge does not show large pulsations when a triplex pump is used.

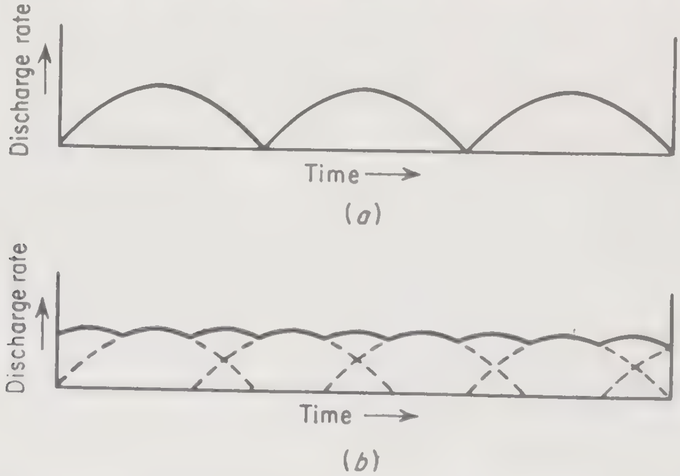

FIG. 14-13. Discharge-rate curves for (*a*) simplex, double-acting pump and (*b*) triplex, single-acting pump.

The theoretical fluid displacement of a piston pump equals the total volume swept by the piston on each delivery stroke. Because of leakage past the piston and the valves and failure of the valves to close instantly, this theoretical displacement is not attained in actual practice. The *volumetric efficiency*, defined as the ratio of the actual displacement to the theoretical displacement, is usually in the range of 70 to 95 per cent.

When a steam pump is used, the pressure of the steam in pounds per unit area times the area of the piston would be the maximum force that could be exerted on the work-delivery piston if the machine were perfect and no friction were involved. However, friction is involved and work must be done on the liquid (or work-receiving fluid) under conditions in which the steam pressure is a finite amount greater than the liquid pressure. The ratio of the pressure theoretically required on the steam piston to the pressure actually exerted by the steam is known as the *pressure efficiency* or *steam-end efficiency*. It includes the effects of piston and rod friction, momentum changes in acceleration of the piston and fluid, and leakage of fluid past the piston. The pressure efficiency varies from about 50 per cent for small pumps up to 80 per cent for large pumps.

Another so-called efficiency, known as *hydraulic efficiency*, is sometimes given for reciprocating pumps. This efficiency indicates losses due to velocity changes in the inlet and outlet of the pump, friction, and valves. It is defined as the ratio of the actual head across the pump to the sum of the actual head pumped and the losses in the suction and discharge lines.

For pumps driven by electric motors, over-all efficiency is usually defined as the work done on the fluid divided by the electrical energy supplied to the motor. Attempts to apply this type of definition to the over-all efficiency of steam pumps can give misleading results because the term "energy supplied by the steam" can have many meanings. For design estimates, an over-all efficiency for steam pumps is sometimes defined as the work done on the fluid divided by the ideal work that could have been obtained by the isentropic expansion of the steam from its initial temperature and pressure to its exhaust pressure.* The numerical value of this type of over-all efficiency is significant only when the operating conditions are specified for the particular pump.

Reciprocating pumps, in general, have the advantage of being able to deliver fluids against high pressures and operate with good efficiency over a wide range of operating conditions. A major disadvantage of piston and plunger pumps is that they cannot be used with fluids which contain abrasive solids. Reciprocating diaphragm pumps, however, are satisfactory for handling fluids with large amounts of suspended solids at low heads.

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* R. M. Braca and J. Happel, *Chem. Eng.*, **60**(1):180 (1953).

Rotary Positive-displacement Pumps. Pumps of this type combine a rotary motion with a positive displacement of the fluid. A common type of rotary gear pump is illustrated in Fig. 14-14. Two intermeshing gears are fitted into a casing with a sufficiently close spacing to seal off effectively each separate tooth space. As the gears rotate in opposite directions, fluid is trapped in each tooth space and is delivered to the exit side of the pump. Similar results can be obtained by using a rotating eccentric cam or separately driven impellers having several lobes.

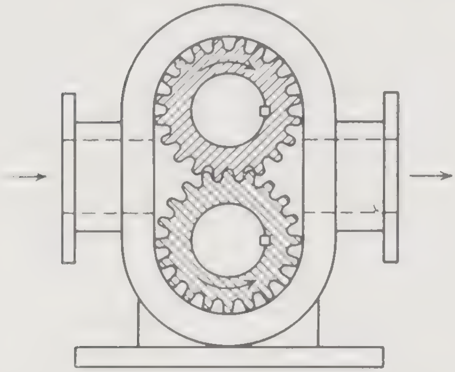

FIG. 14-14. Cutaway view of external gear (rotary) pump.

No priming is required with rotary positive pumps, and they are well adapted for pumping highly viscous fluids. A constant rate of delivery is obtained, and the fluid may be delivered at high pressures. Because of the small clearance that must be maintained, this type of pump should not be used with nonlubricating fluids or with fluids containing solid particles.

Rotary Centrifugal Pumps. In a centrifugal pump, as illustrated in Fig. 14-15, the fluid is fed into the pump at the center of a rotating impeller and is thrown outward by centrifugal force. The fluid at the outer periphery of the impeller attains a high velocity and, consequently, high kinetic energy. The conversion of this kinetic energy into pressure energy

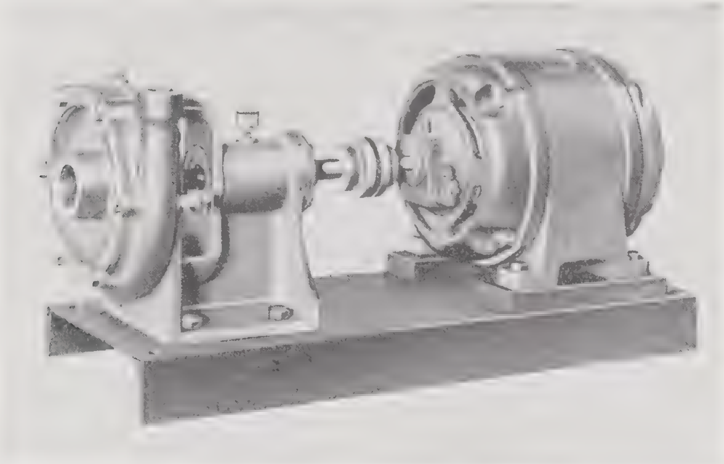

FIG. 14-15. Centrifugal pump and motor. (*Worthington Pump and Machinery Corporation.*)

supplies the pressure difference between the suction side and the delivery side of the pump.

Different forms of impellers are used in centrifugal pumps. One common type, known as a *closed impeller*, consists of a series of curved vanes attached to a central hub and extending outward between two enclosing plates. An open impeller is similar, except that there are no enclosing plates. Impellers of this type are used in *volute pumps*, which are the simplest form of centrifugal pumps.

Energy losses caused by turbulence at the point where the liquid path changes from radial flow to tangential flow in the pump casing can be decreased by using so-called *turbine pumps*. With this type of centrifugal pump, the liquid flows from the impeller through a series of fixed vanes forming a diffusion ring. The change in direction of the fluid is more gradual than in a volute pump, and a more efficient conversion of kinetic energy into pressure energy is obtained.

For an ideal centrifugal pump, the speed of the impeller (N rpm) should be directly proportional to the rate of fluid discharge (q gpm), or

$$\frac{N_1}{N_2} = \frac{q_1}{q_2} \tag{19}$$

The head (or pressure difference) produced by the pump is a function of the kinetic energy developed at the point of release from the impeller. The head developed by an ideal pump, therefore, should be directly proportional to the square of the impeller speed:

$$\frac{\text{Head}_1}{\text{Head}_2} = \frac{{q_1}^2}{{q_2}^2} = \frac{{N_1}^2}{{N_2}^2} \tag{20}$$

The power required for a perfect pump is directly proportional to the product of the head and the flow rate; therefore,

$$\frac{\text{Power}_1}{\text{Power}_2} = \frac{{q_1}^3}{{q_2}^3} = \frac{{N_1}^3}{{N_2}^3} \tag{21}$$

The preceding equations apply for the ideal case in which there are no frictional, leakage, or recirculation losses. In any real pump, however, these losses do occur, and their magnitudes can be determined only by actual tests. As a result, characteristic curves are usually supplied by pump manufacturers to indicate the performance of any particular centrifugal pump. Figure 14-16 shows a typical set of characteristic curves for a centrifugal pump.

The ratings of centrifugal pumps are ordinarily based on the head and capacity at the point of maximum efficiency. The size of the pump is usually specified as the diameter of the discharge opening. The rating for the

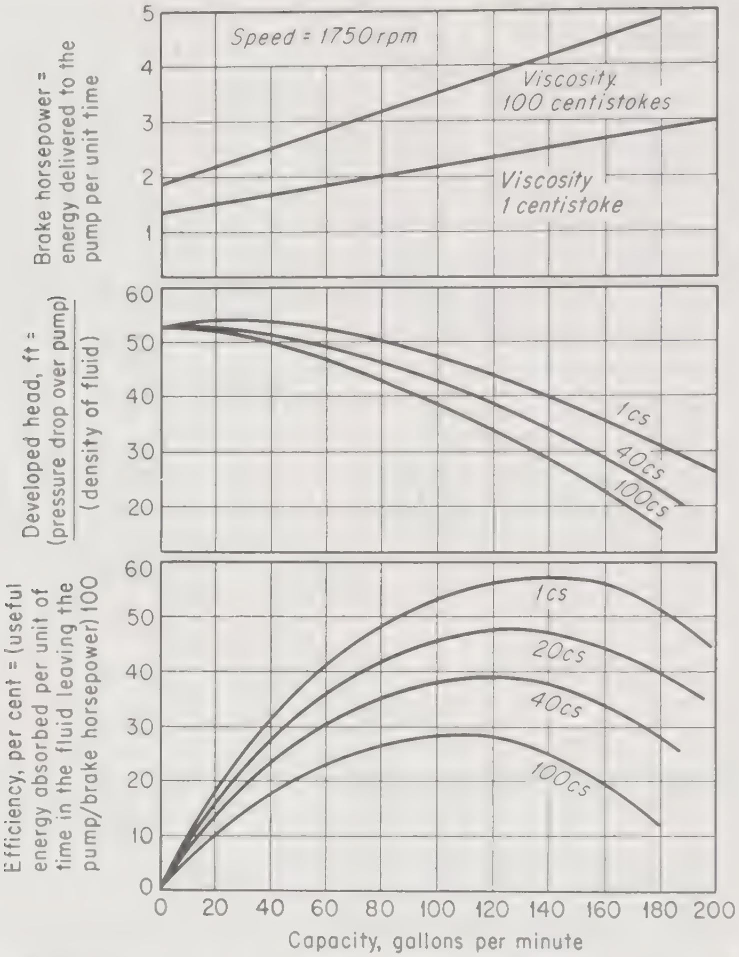

FIG. 14-16. Characteristic curves for a typical centrifugal pump showing effect of fluid viscosity.

pump referred to in Fig. 14-16 would be 140 gpm and a head of 40 ft if water is the fluid involved. From the data shown in Fig. 14-16, if the head is increased to 50 ft, the capacity will decrease to 80 gpm and the efficiency of the pump will decrease. The capacity could be decreased to 80 gpm at a head of 40 ft by throttling the discharge so that a head of 50 ft is actually generated within the pump, but this would result in a reduction of the pump efficiency. Consequently, the design engineer should always attempt to give the necessary pump specifications as accurately as possible in order to obtain the correct pump which will operate at maximum efficiency.

Figure 14-17 gives values that are suitable for design estimates of centrifugal-pump efficiencies. Because pump and driver efficiencies must both be considered when total power costs are determined, necessary design data on the efficiency of electric motors are presented in Fig. 14-18.

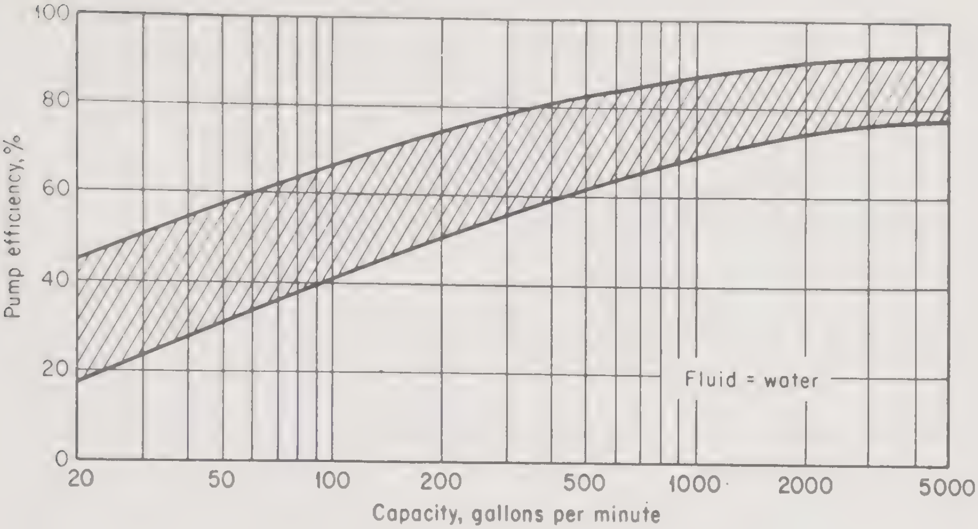

FIG. 14-17. Efficiencies of centrifugal pumps.

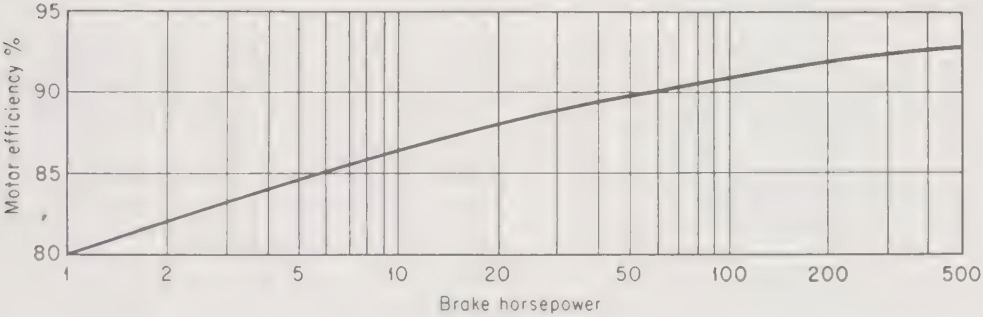

FIG. 14-18. Efficiencies of three-phase electric motors.

The following list gives the major advantages and disadvantages of centrifugal pumps:

Advantages

1. They are simple in construction and cheap.
2. Fluid is delivered at uniform pressure without shocks or pulsations.
3. They can be coupled directly to motor drives. In general, the higher the speed, the smaller the pump and motor required for a given duty.
4. The discharge line may be partly shut off or completely closed off without damaging the pump.
5. They can handle liquid with large amounts of solids.
6. There are no close metal-to-metal fits.
7. There are no valves involved in the pump operation.
8. Maintenance costs are lower than for other types of pumps.

Disadvantages

1. They cannot be operated at high heads.
2. They are subject to air binding and usually must be primed.
3. The maximum efficiency for a given pump holds over a fairly narrow range of conditions.
4. They cannot handle highly viscous fluids efficiently.

Air-displacement Systems. The pumps discussed in the preceding sections depend on the mechanical action of pistons, impellers, plungers, or other devices to move the fluid. Movement of fluids can also be accomplished by the use of air pressure, and many types of air-displacement systems have been developed for this purpose. The most common of these systems are air lifts, acid eggs, and jet pumps.

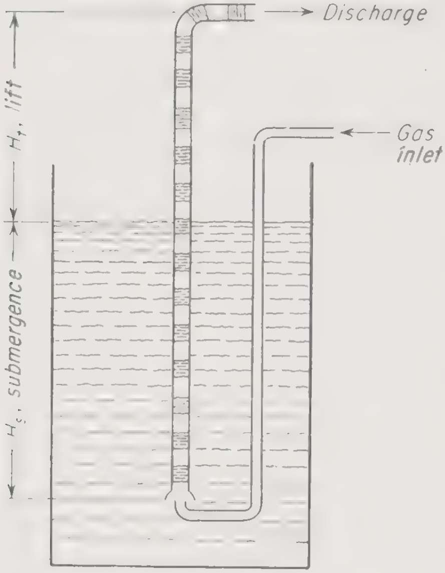

FIG. 14-19. Diagram showing operating principle of a simple air lift.

A diagram of a simple *air lift* is shown in Fig. 14-19. Compressed air is introduced into the submerged end of the discharge pipe at a distance of H_s ft below the liquid surface. Because the air-and-liquid mixture is lighter than the liquid alone, the mixture rises through the discharge pipe and is expelled into an overhead receiver at a distance of H_l ft above the liquid surface. Although equations for the operation of an air lift can be developed theoretically,* the frictional effects are so complex that the following empirical equation is usually assumed for the design basis: †

$$V_{\text{air}} = 0.8 \frac{H_l}{C_a \log [(H_s + 34)/34]} \tag{22}$$

where V_{air} is the cubic feet of free air (i.e., at normal atmospheric conditions) required to raise 1 gal of water, and C_a has the following values:

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* J. M. Coulson and J. F. Richardson, "Chemical Engineering," vol. I, McGraw-Hill Book Company, Inc., New York, 1954.

† F. W. O'Neil, "Compressed Air Data," 5th ed., pp. 188–191, Ingersoll-Rand Company, New York, 1954.

H_t, ft	Recommended value of $H_s/(H_s + H_t)$	C_a (outside air line)
20–125	0.65	348
126–250	0.60	335
251–400	0.50	296
401–650	0.40	246
651–700	0.35	216

Acid eggs or *blow cases* are simply closed vessels with inlet and outlet lines and an air connection. Air is admitted to the vessel and forces the liquid out through the discharge line. Operation of acid eggs is intermittent, and the elevation attained depends on the air pressure. Although these systems are inexpensive and easy to operate, they are inefficient. Their use is limited primarily to batchwise operations with corrosive fluids.

Jet pumps, employing water, steam, or gas as the operating medium, are often used for transferring fluids. The operating medium flows rapidly through an expanding nozzle and discharges into the throat of a venturi. As the operating medium issues from the nozzle, the high velocity head causes a decrease in the pressure head. If the resulting pressure is less than that of the second fluid at that point, the fluid will be sucked into the venturi throat along with the operating medium and discharged from the venturi outlet.

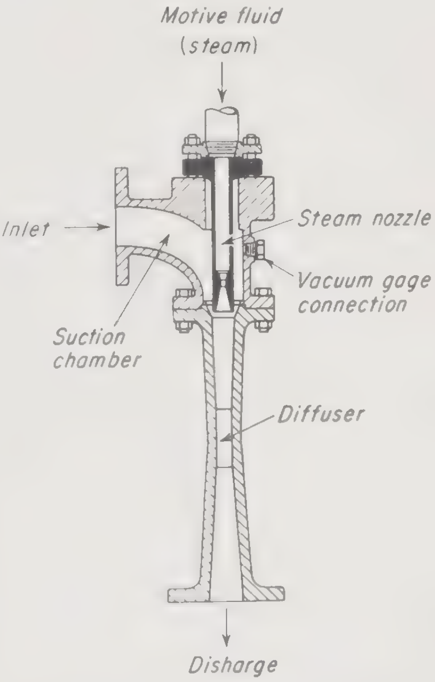

FIG. 14-20. Longitudinal cross-sectional view of a typical steam-jet ejector.

Figure 14-20 illustrates a typical steam-jet ejector. This type of jet pump is used to remove air, gases, or vapors from condensers and vacuum equipment, and the steam jets can be connected in series or parallel to handle larger amounts of gas or to develop a greater vacuum. The capacity of steam-jet ejectors is usually reported as pounds per hour instead of on a volume basis. For design purposes, it is often necessary to make a rough estimate of the steam requirements for various ejector capacities and conditions. The data given in Table 3 can be used for this purpose.

TABLE 3. STEAM-JET AVERAGE CONSUMPTION OF STEAM AT 100 PSIG IN POUNDS PER HOUR *†

For larger or smaller capacities, steam consumption is approximately proportional to the capacity.

Capacity	Wt % net dry air (non-condensables) in gas-vapor mixture	Suction pressure, in. Hg absolute									
		0.5		1.0		1.5	2.0	3.0	4.0		6.0
Wt of gas-vapor mixture handled, lb/hr		3-stage	2-stage	3-stage	2-stage	2-stage	2-stage	2-stage	2-stage	1-stage	1-stage
10	100	73	99	59	70	58	50	42	38	58	36
10	70	59	84	47	60	49	42	35	31	63	39
10	40	45	68	33	47	38	32	26	23	68	41
10	10	24	45	16	28	21	17	14	12	74	42

* J. H. Perry, "Chemical Engineers' Handbook," 3d ed., McGraw-Hill Book Company, Inc., New York, 1950.

† For additional information, see P. Messina, J. J. Brown, and J. Bohnlofink, *Chem. Eng.*, **61**(1):161 (1954); R. Frumerman, *Chem. Eng.*, **63**(6):197 (1956).

Barometric-leg pumps are used for assisting in maintaining a vacuum when condensable vapors are involved. Auxiliary pumps are necessary to remove any fixed gases that may accumulate in the leg. For water condensation, the leg usually empties into an open well, and the vertical length of the leg must be longer than 34 ft.

Gas Compressors.* Movement of gases can be accomplished by use of fans, blowers, vacuum pumps, and compressors. Fans are useful for moving gases when pressure differences less than about 0.5 psi are involved. Centrifugal blowers can handle large volumes of gases, but the delivery pressure is limited to approximately 50 psig. Reciprocating compressors can be employed over a wide range of capacities and pressures, and they are used extensively in industrial operations. Sizes of reciprocating compressors ranging from less than 1 to 3000 hp are available, and some types can give delivery pressures as high as 4000 atm.

Compressor efficiencies are usually expressed as isentropic efficiencies, i.e., on the basis of an adiabatic and reversible process. Isothermal efficiencies are sometimes quoted, and design calculations are simplified when isothermal efficiencies are used. In either case, the efficiency is defined as the ratio of the power required for the ideal process to the power actually consumed.

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* For a series of articles giving detailed information on compressors, see *Chem. Eng.*, vol. 63, no. 6, 1956.

Because the energy necessary for an isentropic compression is greater than that required for an equivalent isothermal compression, the isentropic efficiency is always greater than the isothermal efficiency. For reciprocating compressors, isentropic efficiencies are generally in the range of 60 to 90 per cent and isothermal efficiencies are about 50 to 60 per cent. Multistage compression is necessary for high efficiency in most large compressors if the ratio of the delivery pressure to the intake pressure exceeds approximately 5:1.

Expressions for the theoretical power requirements of gas compressors can be obtained from the basic equations of thermodynamics. For an ideal gas undergoing an isothermal compression (pv = constant), the theoretical power requirement for any number of stages can be expressed as follows:

$$\text{Power} = p_1 v_1 \ln \frac{p_2}{p_1} \tag{23}$$

or

$$\text{hp} = 3.03 \times 10^{-5} p_1 q_{fm_1} \ln \frac{p_2}{p_1} \tag{24}$$

where Power = power requirement, ft-lb force/lb mass
p_1 = intake pressure, lb force/sq ft
v_1 = specific volume of gas at intake conditions, cu ft/lb mass
p_2 = final delivery pressure, lb force/sq ft
q_{fm_1} = cubic feet of gas per minute at intake conditions

Similarly, for an ideal gas undergoing an isentropic compression (pv^k = constant), the following equations apply:

For single-stage compressor

$$\text{Power} = \frac{k}{k-1} p_1 v_1 \left[\left(\frac{p_2}{p_1} \right)^{(k-1)/k} - 1 \right] \tag{25}$$

$$\text{hp} = \frac{3.03 \times 10^{-5} k}{k-1} p_1 q_{fm_1} \left[\left(\frac{p_2}{p_1} \right)^{(k-1)/k} - 1 \right] \tag{26}$$

$$p_2 = p_1 \left(\frac{v_1}{v_2} \right)^k = p_1 \left(\frac{T_2}{T_1} \right)^{k/(k-1)} \tag{27}$$

$$T_2 = T_1 \left(\frac{v_1}{v_2} \right)^{k-1} = T_1 \left(\frac{p_2}{p_1} \right)^{(k-1)/k} \tag{28}$$

For multistage compressor, assuming equal division of work between cylinders and intercooling of gas to original intake temperature,

$$\text{hp} = \frac{3.03 \times 10^{-5} k N_s}{k-1} p_1 q_{fm_1} \left[\left(\frac{p_2}{p_1} \right)^{(k-1)/kN_s} - 1 \right] \tag{29}$$

$$T_2 = T_1 \left(\frac{p_2}{p_1} \right)^{(k-1)/kN} \tag{30}$$

where k = ratio of specific heat of gas at constant pressure to specific heat of gas at constant volume

v_2 = specific volume of gas at final delivery conditions, cu ft/lb mass

T_1 = absolute temperature of gas at intake conditions, °R

T_2 = absolute temperature of gas at final delivery conditions, °R

N_s = number of stages of compression

Cost of Pumping Machinery. Figures 14-21 through 14-23 give approximate costs for different types of pumps, compressors, blowers, fans and motors. Although the data from these figures can be used for preliminary design estimates, firm estimates should be based on manufacturers quotations.

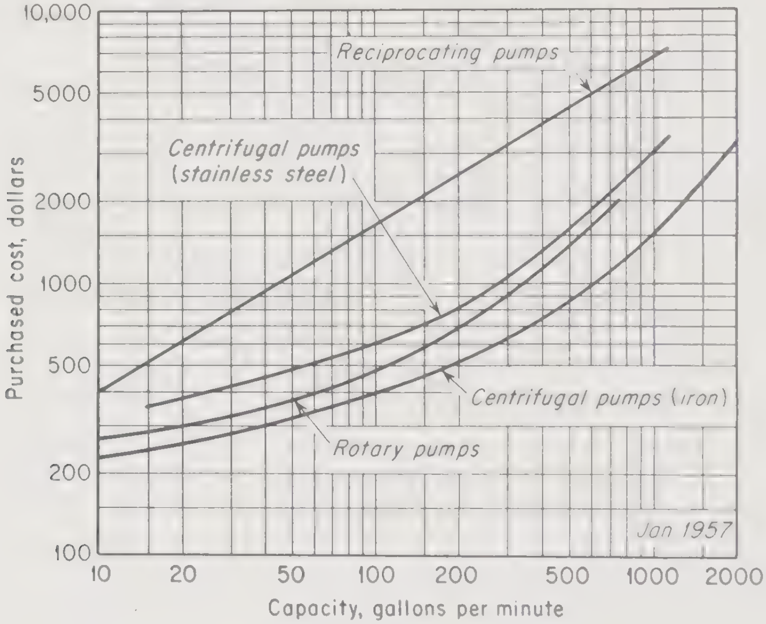

FIG. 14-21. Cost of centrifugal, rotary, and reciprocating pumps.

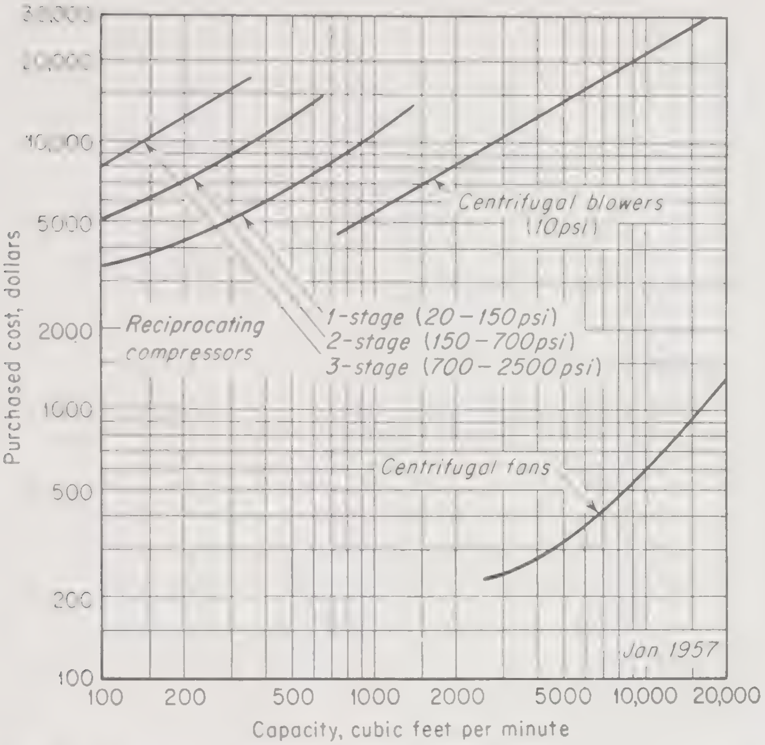

FIG. 14-22. Cost of reciprocating compressors, centrifugal blowers, and centrifugal fans.

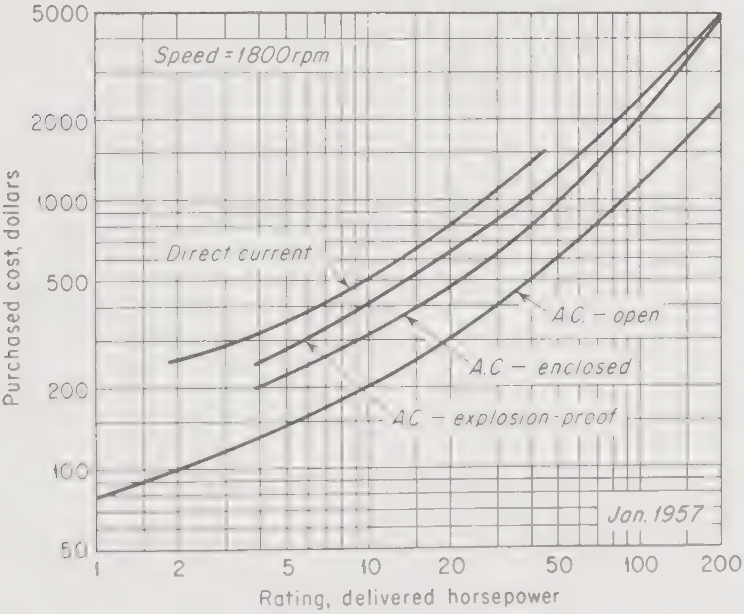

FIG. 14-23 Cost of electric motors.

FLOW-MEASURING EQUIPMENT

Orifice meters, venturi meters, rotameters, and displacement meters are used extensively in industrial operations for measuring the rate of fluid flow. Other flow-measuring devices, such as weirs, pitot tubes, anemometers, and wet-test meters, are also useful in industrial operations.* In general, orifice meters are the cheapest and most flexible of the various types of equipment for measuring flow rates. Despite the inherent disadvantage of large permanent pressure drops with orifice installations, they are one of the most common types of flow-measuring equipment in industrial operations. Venturi meters are expensive and must be carefully proportioned and fabricated. However, they do not cause a large permanent pressure drop and are, therefore, very useful when power cost is an important factor.

Basic equations for the design and operation of orifice meters, venturi meters, and rotameters can be derived from the total energy balances presented at the beginning of this chapter. The following equations apply when the flowing fluid is a liquid, and they also give accurate results for the flow of gases if the pressure drop caused by the constriction is less than 5 per cent of the upstream pressure:

For orifice meters and venturi meters

$$q_f = CS_c \sqrt{\frac{2g_c v(p_1 - p_c)}{1 - (S_c/S_1)^2}} \tag{31}$$

For rotameters

$$q_f = CS_c \sqrt{\frac{V_p 2g(\rho_p - 1/v)v}{S_p[1 - (S_c/S_1)^2]}} \tag{32}$$

where q_f = flow rate, cfs
C = coefficient of discharge
S_c = cross-sectional flow area at point of minimum cross-sectional flow area, sq ft
S_1 = cross-sectional flow area in upstream section of duct before constriction, sq ft
g_c = gravitational constant in Newton's law of motion, 32.17 ft-lb mass/(sec)(sec)(lb force)

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* Detailed descriptions of various types of flow-measuring equipment and derivations of related equations are presented in essentially all books dealing with chemical engineering principles. See G. G. Brown et al., "Unit Operations," John Wiley & Sons, Inc., New York, 1950; and J. H. Perry, "Chemical Engineers' Handbook," 3d ed., McGraw-Hill Book Company, Inc., New York, 1950.

g = local gravitational acceleration, ft/(sec)(sec)
v = average specific volume of fluid, cu ft/lb
p_1 = static pressure in upstream section of duct before constriction, psf
p_c = static pressure at point of minimum cross-sectional flow area, psf
V_p = volume of plummet, cu ft
S_p = maximum cross-sectional area of plummet, sq ft
ρ_p = density of plummet, lb/cu ft

The value of the coefficient of discharge C for orifice meters depends on the properties of the flow system, the ratio of the orifice diameter to the upstream diameter, and the location of the pressure-measuring taps. Values of C for sharp-edged orifice meters are presented in Fig. 14-24. These values apply strictly for pipe orifices with *throat taps*, in which the downstream pressure tap is located one-third of one pipe diameter from the downstream side of the orifice plate and the upstream tap is located one pipe diameter from the upstream side. However, within an error of about 5 per cent, the values of C indicated in Fig. 14-24 may be used for manometer taps located anywhere between the orifice plate and the hypothetical throat taps.

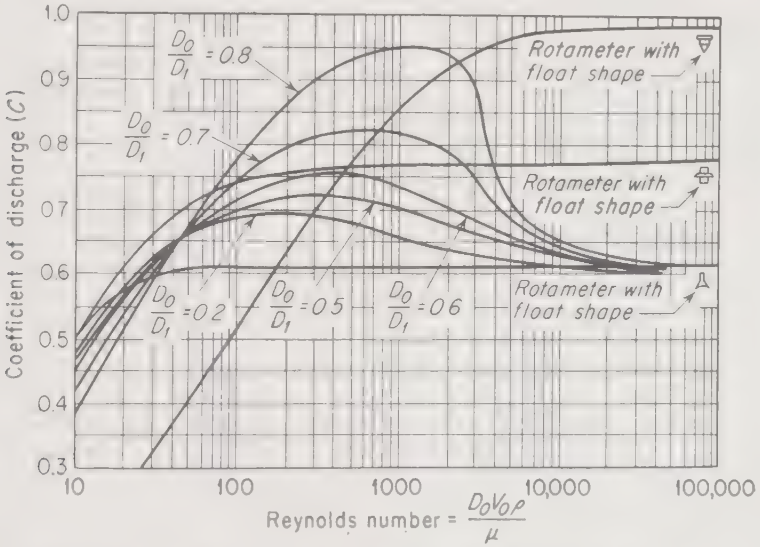

FIG. 14-24. Coefficients of discharge for square-edged orifices with centered circular openings and for rotameters. (*Subscript o indicates "at orifice or at constriction," and subscript 1 indicates "at upstream section."*)

Venturi meters usually have a tapered entrance with an interior total angle of 25 to 30° and a tapered exit with an interior angle of 7°. Under these conditions, the value of the coefficient of discharge may be assumed to be 0.98 if the Reynolds number based on conditions in the upstream section is greater than 5000.

Values of C for various plummet shapes in rotameters are presented in Fig. 14-24.* The Reynolds number applicable to the rotameter coefficient of discharge is based on the flow conditions through the annular opening between the plummet and the containing tube. The equivalent diameter for use in the Reynolds number is the difference between the diameter of the rotameter tube at the plummet location and the maximum diameter of the plummet.

TANKS AND STORAGE EQUIPMENT

Storage of liquid materials is commonly accomplished in industrial plants by use of cylindrical, spherical, or rectangular tanks. These tanks may be constructed of wood, concrete, or metal, with metal being the most common material of construction. The design of storage vessels involves con-

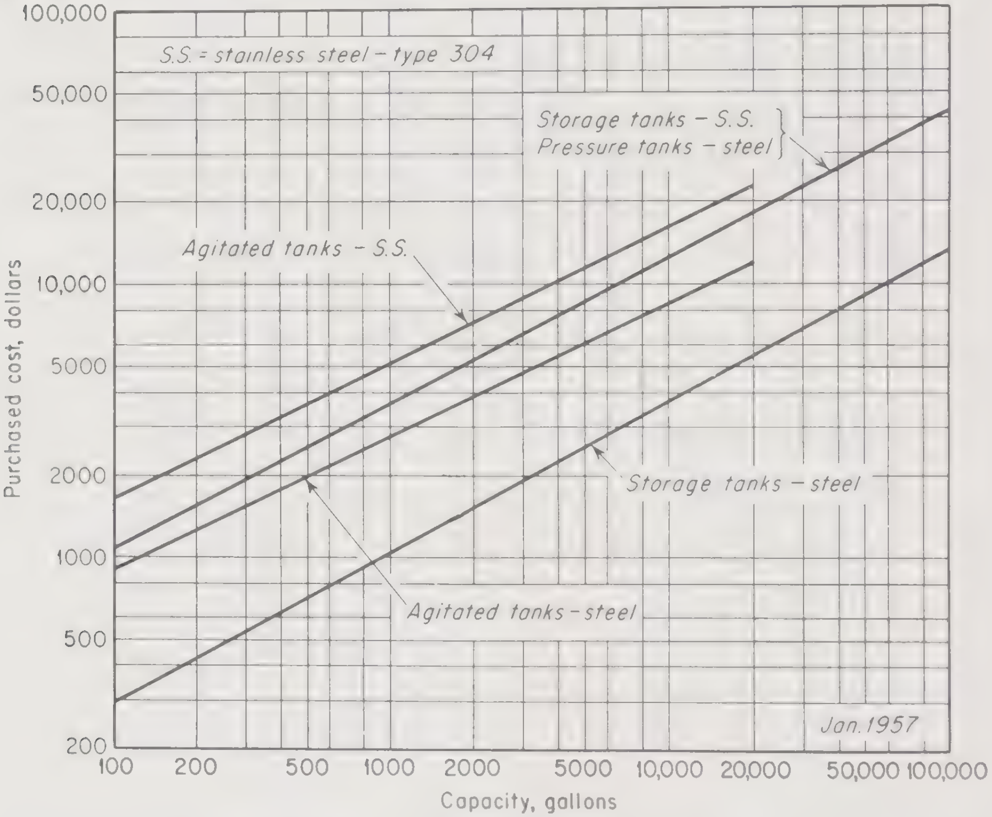

FIG. 14-25. Cost of agitated tanks (including driving unit), storage tanks, and pressure tanks (cylindrical, 200 psig, or spherical, 100 psig).

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* Fischer and Porter Company, Catalog Section 98-A, Hatboro, Pa., 1947.

TABLE 4. DESIGN EQUATIONS FOR PRESSURE VESSELS *†

For pressures up to 3000 psi

t_m = minimum wall thickness, in.
P = maximum allowable internal pressure, psig
S = maximum allowable working stress, psi
E_J = efficiency of joints expressed as a fraction
C_c = allowance for corrosion, in.
r_o = outside radius of shell, in.
r_i = inside spherical or crown radius of head, in.

Recommended design equations for vessels under internal pressure	Limiting conditions
For cylindrical shells $t_m = \frac{Pr_o}{SE_J + 0.4P} + C_c$	$t_m \leqq 0.5r_o$ or $P \leqq 0.385SE_J$
For spherical shells $t_m = \frac{Pr_o}{2SE_J + 0.8P} + C_c$	$t_m \leqq 0.356r_o$ or $P \leqq 0.665SE_J$
For spherically dished heads $t_m = \frac{0.885Pr_i}{SE_J - 0.1P} + C_c$	Knuckle radius = 6% of inside crown radius
For hemispherical heads $t_m = \frac{Pr_i}{2SE_J - 0.2P} + C_c$	$t_m \leqq 0.356r_i$ or $P \leqq 0.665SE_J$

Joint efficiencies	Recommended stress values		
	Metal	Temp., °F	S, psi
Lap-welded and butt-welded with backing strip = 80 to 90%	Carbon steel (SA-30-flange)	−20–650	13,750
		750	12,050
		850	8,350
	Stainless steel (type 304)	−20–100	18,750
Butt-welded with no backing strip = 70 to 75%		600	14,900
		1000	12,500
	Stainless steel (type 316)	−20–100	18,750
		600	17,100
		1000	14,000
	Copper (SB-11)	150	6,700
		400	2,500
	Aluminum (SB-179, 996A, O)	100	1,650
		400	1,050

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* Based on 1952 ASME Code for Unfired Pressure Vessels.

† C. J. Major, Charts for Pressure Vessel Design, *Chem. Eng.*, **62**(4):172 (1955).

sideration of details such as size and number of openings, shape of heads, necessary temperature and pressure controls, and corrosive action of the contents. One of the major factors in the design is the wall thickness. The wall must be sufficiently thick to permit safe usage under all operating conditions.

The necessary wall thickness for metal vessels is a function of (1) the ultimate tensile strength or the yield point of the metal at the operating temperatures, (2) the operating pressure, (3) the diameter of the tank, and (4) the joint or welding efficiencies.* Various codes are available which specify the conditions that must be met for different vessels. A summary of design equations and other information based on the ASME Code for Unfired Pressure Vessels is presented in Table 4.

Cost data for agitated tanks,† storage tanks, and pressure tanks are shown in Fig. 14-25.

NOMENCLATURE FOR CHAP. 14

C = coefficient of discharge for orifice or rotameter
C_a = coefficient in air-lift design equation
C_c = allowance for corrosion, in.
C_p = heat capacity at constant pressure, Btu/(lb mole)(°F)
D = diameter, ft
D_i = inside diameter, in.
D_m = mean diameter, in.
D_o = orifice diameter, ft
E = efficiency of pump and drive, expressed as a fraction
E_J = efficiency of joints, expressed as a fraction
$\mathfrak{f}$ = Fanning friction factor
F = mechanical-energy loss due to friction, ft-lb force/lb mass
F_c = frictional loss due to sudden contraction, ft-lb force/lb mass
F_e = frictional loss due to sudden expansion, ft-lb force/lb mass
F_i = ratio of total costs for fittings and installation to purchase cost for new pipe
g = local gravitational acceleration, ft/(sec)(sec)
g_c = conversion factor in Newton's law of motion, 32.17 ft-lb mass/(sec)(sec)(lb force)
G = mass velocity, lb mass/(hr)(sq ft of cross-sectional area)
h = enthalpy, ft-lb force/lb mass
H_s = submergence, ft
H_l = lift, ft
H_y = hours of operation per year
J = frictional loss due to fittings and bends, expressed as equivalent fractional loss in a straight pipe
k = ratio of specific heat at constant pressure to specific heat at constant volume

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* In the design of vacuum vessels, the ratio of length to diameter must also be taken into consideration.

† For methods of calculating power requirements for agitators, see J. H. Perry, "Chemical Engineers' Handbook," 3d ed., p. 1224, McGraw-Hill Book Company, Inc., New York, 1950; or G. G. Brown et al., "Unit Operations," p. 506, John Wiley & Sons, Inc., New York, 1950.

K = cost of power, \$/kwhr
K_c = coefficient in expression for frictional loss due to sudden contraction
K_F = annual fixed charges including maintenance, expressed as a fraction of the initial cost for the completely installed piping system
L = length, ft
L_e = fictitious length of straight pipe equivalent to the resistance of a pipe fitting of same nominal diameter as pipe, ft
M = molecular weight, lb mass
n = a constant with value dependent on type of pipe
N = speed of impeller, rpm
N_{Re} = Reynolds number, equals $DV\rho/\mu$, dimensionless
N_s = number of stages of compression
p = absolute pressure, lb force/sq ft
p_c = static pressure at point of minimum cross-sectional flow area, lb force/sq ft
P = maximum allowable internal pressure, psig
P_b = bursting pressure, psig
P_s = safe working pressure, psig
q = rate of fluid discharge, gpm
q_f = fluid-flow rate, cfs
q_{fm} = fluid-flow rate, cfm
Q = heat energy imparted as such to the fluid system from an outside source, ft-lb force/lb mass
r_i = inside spherical or crown radius of head, in.
r_o = outside radius of shell, in.
R = perfect-gas-law constant, 1545 (lb force/sq ft)(cu ft)/(lb mole)(°R)
R_H = hydraulic radius, ft
S = maximum allowable working stress, lb force/sq in.
S_1 = cross-sectional flow area in upstream section of duct before constriction, sq ft
S_c = cross-sectional flow area at point of minimum cross-sectional flow area, sq ft
S_p = maximum cross-sectional area of plummet, sq ft
S_s = safe working fiber stress, lb force/sq in.
S_T = tensile strength, lb force/sq in.
t_m = minimum wall thickness, in.
T = temperature, °R
u = internal energy, ft-lb force/lb mass
v = specific volume of fluid, cu ft/lb mass
V = average linear velocity, fps
V_{air} = volume of free air required in air lift to raise 1 gal of water, cu ft/gal
V_i = instantaneous or point linear velocity, fps
V_o = average linear velocity through orifice, fps
V_p = volume of plummet, cu ft
W = shaft work, gross work input to the fluid system from an outside source, ft-lb force/lb mass
W_o = mechanical work imparted to the fluid system from an outside source, ft-lb force/lb mass
X = purchase cost of new pipe per foot of pipe length if pipe diameter is 1 in., \$/ft
Z = vertical distance above an arbitrarily chosen datum plane, ft

Greek Symbols

α = alpha, correction coefficient to account for use of average velocity
Δp_f = change in pressure due to friction, lb force/sq ft

ϵ = epsilon, equivalent roughness, ft
μ = mu, absolute viscosity of fluid, lb mass/(ft)(sec)
μ_a = absolute viscosity of fluid at average bulk temperature, lb mass/(ft)(sec)
μ_c = absolute viscosity of fluid, centipoises
μ_w = absolute viscosity of fluid at average temperature of wall, lb mass/(ft)(sec)
ρ = rho, density of fluid, lb mass/cu ft
ρ_p = density of plummet, lb mass/cu ft
ϕ = phi, correction factor for nonisothermal flow = $1.1(\mu_a/\mu_w)^{0.25}$ when DG/μ_a is less than 2100 and $1.02(\mu_a/\mu_w)^{0.14}$ when DG/μ_a is greater than 2100

PROBLEMS

1. A lean oil is to be used as the absorbing medium for removing a component of a gas. As part of the design for the absorption unit, it is necessary to estimate the size of motor necessary to pump the oil to the top of the absorption tower. The oil must be pumped from an open tank with a liquid level 10 ft above the floor and forced through 150 ft of schedule number 40 pipe of 3-in. nominal diameter. There are five 90° elbows in the line, and the top of the tower is 30 ft above the floor level. The operating pressure in the tower is to be 50 psig, and the oil requirement is estimated to be 50 gpm. The viscosity of the oil is 15 centipoises, and its density is 53.5 lb/cu ft. If the efficiency of the pumping assembly including the drive is 40 per cent, what horsepower motor will be required?

2. Hydrogen at a temperature of 20°C and a pressure of 200 psia enters a compressor where the pressure is increased to 600 psia. If the mechanical efficiency of the compressor is 55 per cent on the basis of an isothermal and reversible operation, calculate the pounds of hydrogen that can be handled per minute when the power supplied to the pump is 300 hp. Kinetic-energy effects can be neglected.

3. For the conditions indicated in Prob. 2, determine the mechanical efficiency of the pump on the basis of adiabatic and reversible operation. A single-stage compressor is used, and the ratio of heat capacity at constant pressure to the heat capacity at constant volume for the hydrogen may be assumed to be 1.4.

4. A steel pipe of 4-in. nominal diameter is to be used as a high-pressure steam line. The pipe is butt-welded, and its schedule number is 40. Estimate the maximum steam pressure that can be used safely in this pipe.

5. A preliminary estimate is to be made of the total cost for a completely installed pumping system. A pipeline is to be used for a steady delivery of 250 gpm of water at 60°F. The total length of the line will be 1000 ft, and it is estimated that the theoretical horsepower requirement (100 per cent efficiency) of the pump is 10.0 hp. Using the following additional data, estimate the total installed cost for the pumping system.

Materials of construction—black steel (standard weights are satisfactory)
Number of fittings (equivalent to tees)—40
Number of valves (gate)—4
Insulation—85 per cent magnesia, 1½ in. thick
Pump—centrifugal (no stand-by pump is needed)
Motor—a-c, enclosed, 3-phase, 1800 rpm

6. A centrifugal pump delivers 100 gpm of water at 60°F when the impeller speed is 1750 rpm and the pressure drop across the pump is 20 psi. If the speed is reduced to 1150 rpm, estimate the rate of water delivery and the developed head in feet if the pump operation is ideal.

7. A two-stage steam jet is to be used on a large vacuum system. It is estimated that 20 lb of air must be removed from the system per hour. The leaving vapors will contain water vapor at a pressure equivalent to the equilibrium vapor pressure of water at 60°F. If a suction pressure of 2.0 in. Hg absolute is to be maintained by the jet, estimate the pounds of steam required per hour to operate the jet.

8. The rate of flow of a liquid mixture is to be measured continuously. The flow rate will be approximately 40 gpm, and rates as low as 30 gpm or as high as 50 gpm can be expected. An orifice meter, a rotameter, and a venturi meter are available. On the basis of the following additional information, would you recommend installation of the orifice meter, the venturi meter, or the rotameter? Give reasons for your choice.

Density of liquid = 58 lb/cu ft
Viscosity of liquid = 1.2 centipoises
Diameter of venturi throat = 1 in.
Upstream diameter of venturi opening = 2 in.
Manometers connected across the venturi and the orifice contain a nonmiscible liquid (sp gr = 1.56) in contact with the liquid mixture
The maximum possible reading on these manometers is 15 in.
Orifice is square-edged with throat taps
Diameter of orifice opening = 1 in.
Diameter of upstream chamber for orifice meter = 3 in.

Calibration curve for rotameter is for water at 60°F and gives the following values:

Rotameter reading	*Flow rate, cfm*
2.0	2.0
4.0	4.0
6.0	6.0
8.0	8.0

The density of the plummet in the rotameter is 497 lb/cu ft.

9. A carbon-steel cylindrical storage tank with hemispherical heads has a side length of 36 ft and an inside diameter of 12 ft. All joints are butt-welded with backing strip. If the tank is to be used at a working pressure of 200 psig and a temperature of 80°F, estimate the necessary thickness of the side walls and the heads on the basis of the 1952 ASME Code for Unfired Pressure Vessels. No corrosion allowance is necessary. Compare the side-wall thickness obtained with that obtained on the basis of the 1938 API-ASME Code for Unfired Pressure Vessels. (See Chap. 13, Prob. 6.)

10. Estimate the cost of the steel for the storage tank considered in the preceding problem if the steel sheet costs $0.06 per pound. On the basis of the data presented in Fig. 14-25, estimate the fraction of the purchased cost of the tank that is due to the cost for the steel.

CHAPTER 15

HEAT-TRANSFER EQUIPMENT—DESIGN AND COSTS

Equipment for transferring heat is used in essentially all the process industries, and the design engineer should be acquainted with the many different types of equipment employed for this operation. Although relatively few engineers are involved in the manufacture of heat exchangers, many engineers are directly concerned with specifying and purchasing heat-transfer equipment. Process-design considerations, therefore, are of particular importance to those persons who must decide which piece of equipment is suitable for a given process.

Modern heat exchangers range from simple concentric-pipe exchangers to complex surface condensers with thousands of square feet of heating area. Between these two extremes are found the conventional shell-and-tube exchangers, coil heaters, bayonet heaters, extended-surface exchangers, furnaces, and many varieties of other equipment. Exchangers of the shell-and-tube type are used extensively in industry, and they are often named specifically for distinguishing design features. For example, U-tube, fin-tube, fixed-tubesheet, and floating-head exchangers are common types of shell-and-tube exchangers. Figure 15-1 shows design details of a conventional two-pass exchanger of the shell-and-tube type.

Intelligent selection of heat-transfer equipment requires an understanding of the basic theories of heat transfer and the methods for design calculation. In addition, the problems connected with mechanical design, fabrication, and operation must not be overlooked. An outline of heat-transfer theory and design-calculation methods is presented in this chapter, together with an analysis of the general factors that must be considered in the selection of heat-transfer equipment.

Determination of appropriate coefficients of heat transfer is required for design calculations on heat-transfer operations. These coefficients can sometimes be estimated on the basis of past experience, or they can be calculated from empirical or theoretical equations developed by other workers in the field. Many semiempirical equations for the evaluation of heat-transfer coefficients have been published. Each of these equations has its limitations, and the engineer must recognize the fact that these limitations exist. A summary of useful and reliable design equations for estimating

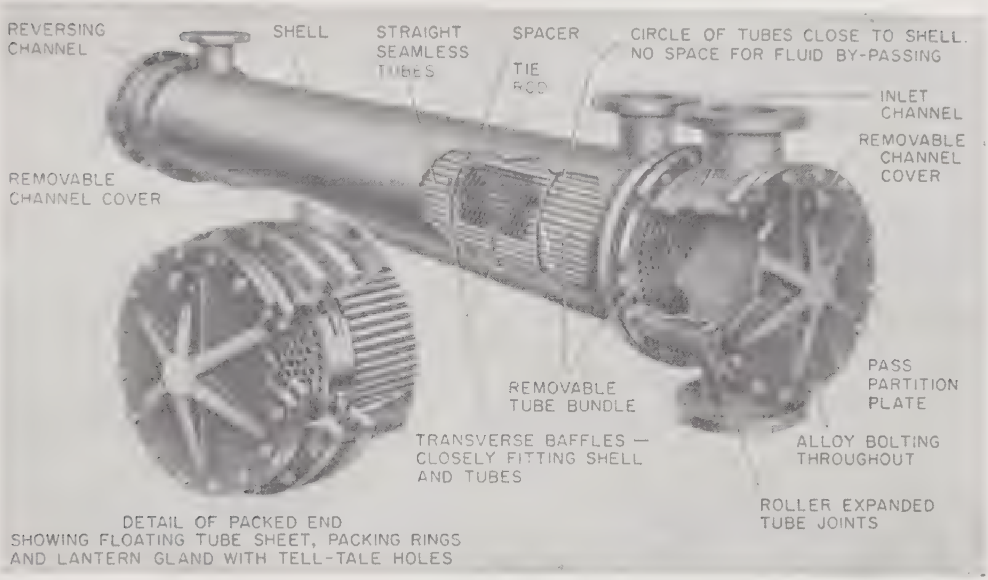
REVERSING CHANNEL
SHELL
STRAIGHT SEAMLESS TUBES
SPACER
TIE ROD
CIRCLE OF TUBES CLOSE TO SHELL. NO SPACE FOR FLUID BY-PASSING
INLET CHANNEL
REMOVABLE CHANNEL COVER
REMOVABLE CHANNEL COVER
PASS PARTITION PLATE
REMOVABLE TUBE BUNDLE
TRANSVERSE BAFFLES — CLOSELY FITTING SHELL AND TUBES
ALLOY BOLTING THROUGHOUT
ROLLER EXPANDED TUBE JOINTS
DETAIL OF PACKED END SHOWING FLOATING TUBE SHEET, PACKING RINGS AND LANTERN GLAND WITH TELL-TALE HOLES

FIG. 15-1. Two-pass shell-and-tube heat exchanger showing construction details. (*Ross Heat Exchanger Division of American-Standard.*)

heat-transfer coefficients under various conditions is presented in this chapter. Additional relations and discussion of special types of heat-transfer equipment and calculation methods are presented in the numerous books and articles that have been published on the general subject of heat transfer.*

BASIC THEORY OF HEAT TRANSFER

Heat can be transferred from a source to a receiver by *conduction*, *convection*, or *radiation*. In many cases, the exchange occurs by a combination of two or three of these mechanisms. When the rate of heat transfer remains constant and is unaffected by time, the flow of heat is designated as being in a *steady state*; an *unsteady state* exists when the rate of heat transfer at any point varies with time. Most industrial operations in which heat transfer is involved are carried out under steady-state conditions. However, unsteady-state conditions are encountered in batch processes, cooling and heating of materials such as metals or glass, and certain types of regeneration, curing, or activation processes.

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* M. Jakob, "Heat Transfer," vol. I, John Wiley & Sons, Inc., New York, 1949.

D. Q. Kern, "Process Heat Transfer," McGraw-Hill Book Company, Inc., New York, 1950.

W. H. McAdams, "Heat Transmission," 3d ed., McGraw-Hill Book Company, Inc., New York, 1954.

P. J. Schneider, "Conduction Heat Transfer," Addison-Wesley Publishing Company, Cambridge, Mass., 1955.

Conduction. The transfer of heat through a fixed material is accomplished by the mechanism known as *conduction*. The rate of heat flow by conduction is proportional to the area available for the heat transfer and the temperature gradient in the direction of the heat-flow path. The rate of heat flow in a given direction, therefore, can be expressed as

$$\frac{dQ}{d\theta} = -kA\frac{dt}{dx} \tag{1}$$

where Q = amount of heat transferred in time θ hr, Btu
k = the proportionality constant, designated as thermal conductivity and defined by Eq. (1), Btu/(hr)(sq ft)(°F/ft)
A = area of heat transfer perpendicular to direction of heat flow, sq ft
t = temperature, °F
x = length of conduction path in direction of heat flow, ft

The thermal conductivity is a property of any given material, and its value must be determined experimentally. For solids, the effect of temperature on thermal conductivity is relatively small. Because the conductivity varies approximately linearly with temperature, adequate design accuracy can be obtained by employing an average value of thermal conductivity based on the arithmetic-average temperature of the given material. Values of thermal conductivities for common materials at various temperatures are listed in the Appendix.

For the common case of steady-state flow of heat, Eq. (1) can be expressed as

$$\frac{Q}{\theta} = q = kA_m\frac{\Delta t}{x} \tag{2}$$

where A_m = mean area of heat transfer perpendicular to direction of heat flow, sq ft
q = rate of heat transfer, Btu/hr
Δt = temperature-difference driving force, °F

Convection. Transfer of heat by physical mixing of the hot and cold portions of a fluid is known as *heat transfer by convection*. The mixing can occur as a result of density differences alone, as in *natural convection*, or as a result of mechanically induced agitation, as in *forced convection*.

The following equation is used as a basis for evaluating rates of heat transfer by convection:

$$\frac{dQ}{d\theta} = hA\,\Delta t_f \tag{3}$$

The proportionality constant h is designated as the heat-transfer coefficient.

and it is a function of the type of agitation and the nature of the fluid. The heat-transfer coefficient, like the thermal conductivity k, is often determined on the basis of experimental data. For steady-state conditions, Eq. (3) becomes

$$q = hA\ \Delta t_f \tag{4}$$

Radiation. When radiant heat energy is transferred from a source to a receiver, the method of heat transfer is designated as *radiation*. The rate at which radiant heat energy is emitted from a source is

$$\frac{dQ}{d\theta} = \sigma\epsilon A T^4 \tag{5}$$

where σ = Stefan-Boltzmann constant *
= 0.1713×10^{-8} Btu/(hr)(sq ft)(°R)^4
ϵ = emissivity of surface
A = exposed-surface area of heat transfer, sq ft
T = absolute temperature, °R

The emissivity depends on the characteristics of the emitting surface and, like the thermal conductivity and the heat-transfer coefficient, must be determined experimentally. Part of the radiant energy intercepted by a receiver is absorbed, and part may be reflected. In addition, the receiver, as well as the source, can emit radiant energy.

The engineer is usually interested in the net rate of heat interchange between two bodies. Some of the radiated energy indicated by Eq. (5) may be returned to the source by reflection from the receiver, and the receiver, of course, emits radiant energy which can be partly or completely absorbed by the source. Equation (5), therefore, must be modified to obtain the net rate of radiant heat exchange between two bodies. The general steady-state equation is

$$q_{\text{from body 1 to body 2}} = 0.171A\left[\left(\frac{T_1}{100}\right)^4 F_{A_1}F_{E_1} - \left(\frac{T_2}{100}\right)^4 F_{A_2}F_{E_2}\right] \tag{6}$$

or, in an alternative form,

$$q_{\text{from body 1 to body 2}} = 0.171A\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] F_A F_E \tag{7}$$

where A represents the area of one of the surfaces, F_A is a correction factor based on the relative orientation of the two surfaces and the surface chosen for the evaluation of A, and F_E is a correction factor based on the emissivities and absorptivities of the surfaces.

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* J. A. Bearden and H. M. Watts, *Phys. Rev.*, **81**:73–81 (1951). Earlier references have commonly listed the experimental value of σ as 0.173×10^{-8} Btu/(hr)(sq ft)(°R)^4.

Table 1 indicates methods for evaluating F_A and F_E for several simple cases. Table 2 lists the emissivities of surfaces commonly encountered in industrial operations. Additional tables, plots, and methods for evaluating the correction factors are available in the various texts and handbooks on heat transfer.

TABLE 1. VALUES OF F_A AND F_E FOR USE IN EQ. (7)

ϵ_1 = emissivity of surface 1
ϵ_2 = emissivity of surface 2

Assumptions: Base area is smooth and no direct self-radiation is intercepted by the base surface; separating medium between surfaces is nonabsorbing; emissivity is equal to absorptivity.

Orientation of surfaces	Area, A	F_A	F_E
Surface A_1 small compared with the totally enclosing surface A_2 (for example, heat loss from equipment to surroundings)................	A_1	1	ϵ_1
Two parallel planes of equal area when length and width are large compared with distance between planes	A_1 or A_2	1	$\dfrac{1}{\dfrac{1}{\epsilon_1}+\dfrac{1}{\epsilon_2}-1}$
Surface A_1 is a sphere with radius r_1 inside a concentric sphere with radius r_2	A_1	1	$\dfrac{1}{\dfrac{1}{\epsilon_1}+\left(\dfrac{r_1}{r_2}\right)^2\left(\dfrac{1}{\epsilon_2}-1\right)}$
Surface A_1 is a cylinder with radius r_1 inside a concentric cylinder with radius r_2 when length is large compared with diameter	A_1	1	$\dfrac{1}{\dfrac{1}{\epsilon_1}+\dfrac{r_1}{r_2}\left(\dfrac{1}{\epsilon_2}-1\right)}$

The design engineer often encounters the situation in which a nonblack body is surrounded completely by a large enclosure containing a nonabsorbing gas. An example would be a steam line exposed to the atmosphere. Under these conditions, little error is introduced by assuming that none of the heat radiated from the source is reflected to it, and Eq. (6) or (7) can be simplified to

$$q_{\text{radiated from pipe}} = 0.171A_1\epsilon_1\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] \tag{8}$$

where subscript 1 refers to the pipe and subscript 2 refers to the surroundings. It is often convenient to use Eq. (8) in the following form, analogous to the equation for heat transfer by convection:

$$q_{\text{radiated from pipe}} = h_rA_1\,\Delta t_f = h_rA_1(T_1 - T_2) \tag{9}$$

TABLE 2. NORMAL EMISSIVITIES OF VARIOUS SURFACES

Surface	Temperature, °F	Emissivity
Aluminum, polished plate	73	0.040
Aluminum, rough plate	78	0.055
Aluminum paint	...	0.3–0.6
Aluminum-surfaced roofing	100	0.22
Asbestos paper	100	0.93
Brass, dull	120–660	0.22
Brass, polished	100–600	0.096
Brick, building	...	0.80–0.95
Brick, refractory	...	0.75–0.90
Copper, oxidized	77	0.78
Iron, cast plate, smooth	73	0.80
Iron, oxidized	212	0.74
Iron, polished	800	0.14
Lead, gray, oxidized	75	0.28
Nickel, pure, polished	440	0.07
	710	0.087
Oil paint	212	0.92–0.96
Roofing paper	69	0.91
Silver, polished	100	0.022
	700	0.031
Steel, polished	212	0.066
Steel sheet, oxidized	75	0.80
Water	32	0.95
	212	0.963
Zinc, galvanized sheet iron, gray oxidized	75	0.276

where h_r is a fictitious heat-transfer coefficient based on the rate at which radiant heat leaves the surface of the pipe. Combination of Eqs. (8) and (9) gives

$$h_r = \frac{0.171\epsilon_1\,[(T_1/100)^4 - (T_2/100)^4]}{T_1 - T_2} \tag{10}$$

Equations (8), (9), and (10) are based on the assumption that none of the heat radiated from the source is reflected to it. This, of course, implies that the air surrounding the pipe has no effect. In other words, air is assumed to be nonabsorbing and nonreflecting. This assumption is essentially correct for gases such as oxygen, nitrogen, hydrogen, and chlorine. Other gases, however, such as carbon monoxide, carbon dioxide, sulfur dioxide, ammonia, organic gases, and water vapor, exhibit considerable ability to absorb radiant energy in certain regions of the infrared spectrum. As a result, the design engineer who is dealing with heat transfer in furnaces or other equipment in which absorbing gases are present may find it necessary to consider radiation from gases, as well as ordinary surface radiation.*

Example 1. Combined Heat Transfer by Convection and Radiation. The OD of an uninsulated steam pipe is 1.5 in. The outside-surface temperature of the pipe is constant at 300°F, and the pipe is located in a large room where the surrounding temperature is constant at 70°F. The heat content of the steam is valued at \$0.50 per 10^6 Btu. The emissivity of the pipe surface is 0.7, and the heat-transfer coefficient for heat loss from the surface by convection is 1.4 Btu/(hr)(sq ft)(°F). Under these conditions, determine the cost per year for heat losses from the uninsulated pipe if the length of the pipe is 100 ft.

Solution

From Eq. (4), heat loss by convection $= hA\,\Delta t_f$

$$A = \frac{(3.14)(4.5)(100)}{12} = 118 \text{ sq ft}$$

$$\Delta t_f = 300 - 70 = 230°\text{F}$$

$$q_{\text{convection}} = (1.4)(118)(230) = 38{,}000 \text{ Btu/hr}$$

From Eq. (8),

$$\text{Heat lost by radiation} = 0.171 A_1 \epsilon_1 \left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right]$$

$$= (0.171)(118)(0.7)\left[\left(\frac{300 + 460}{100}\right)^4 - \left(\frac{70 + 460}{100}\right)^4\right]$$

$$= 36{,}000 \text{ Btu/hr}$$

Yearly cost for heat losses per 100 ft of pipe

$$= \frac{(38{,}000 + 36{,}000)(24)(365)(0.5)}{10^6} = \$324$$

Over-all Coefficients of Heat Transfer

Many of the important cases of heat transfer involve the flow of heat from one fluid through a solid retaining wall into another fluid. This heat must flow through several resistances in series. The net rate of heat transfer can be related to the total temperature-difference driving force by employing an over-all coefficient of heat transfer U; thus, for steady-state conditions,

$$q = UA\,\Delta t_{oa} \tag{11}$$

where Δt_{oa} represents the total temperature-difference driving force. Because there are usually several possible areas on which the numerical value of the over-all coefficient can be based, the units of U should include a designation of the base area A. For example, if an over-all coefficient is

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* For calculation methods with nonluminous gases, see W. H. McAdams, "Heat Transmission," 3d ed., McGraw-Hill Book Company, Inc., New York, 1954.

TABLE 3. INDIVIDUAL HEAT-TRANSFER COEFFICIENTS TO ACCOUNT FOR FOULING *

	h_d for water, Btu/(hr)(sq ft)(°F)			
Temperature of heating medium:	Up to 240°F		240–400°F	
Temperature of water:	125°F or less		Above 125°F	
Water velocity, fps:	3 and less	Over 3	3 and less	Over 3
Distilled	2000	2000	2000	2000
Sea water	2000	2000	1000	1000
Treated boiler feedwater	1000	2000	500	1000
Treated make-up for cooling tower	1000	1000	500	500
City, well, Great Lakes	1000	1000	500	500
Brackish, clean river water	500	1000	330	500
River water: muddy, silty †	330	500	250	330
Hard (over 15 grains/gal)	330	330	200	200
Chicago Sanitary Canal	130	170	100	130

	h_d for miscellaneous process services, Btu/(hr)(sq ft)(°F)
Organic vapors, liquid gasoline	2000
Refined petroleum fractions (liquid), organic liquids, refrigerating liquids, brine, oil-bearing steam	1000
Distillate bottoms (above 25°API), gas oil or liquid naphtha below 500°F, scrubbing oil, refrigerant vapors, air (dust)	500
Gas oil above 500°F, vegetable oil	330
Liquid naphtha above 500°F, quenching oils	250
Topped crude (below 25°API), fuel oil	200
Cracked residuum, coke-oven gas, illuminating gas	100

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* "Standards of Tubular Exchanger Manufacturers Association," 3d ed., New York, 1952.

† Mississippi, Schuylkill, Delaware, and East Rivers and New York Bay.

based on the inside area of a pipe, the units of this U should be expressed as Btu/(hr)(sq ft of inside area)(°F).

The over-all coefficient (including a dirt or fouling resistance) can be related to the individual coefficients or resistances by the following equation:

$$\frac{1}{U_d} = \frac{A}{h'A'_f} + \frac{A}{h''A''_f} + \frac{Ax_w}{kA_{mw}} + \frac{A}{h'_dA'_f} + \frac{A}{h''_dA''_f} \tag{12}$$

where A represents the base area chosen for the evaluation of U_d, and the primes refer to the different film resistances involved.

Fouling Factors. After heat-transfer equipment has been in service for some time, dirt or scale may form on the heat-transfer surfaces, causing additional resistance to the flow of heat. To compensate for this possibility, the design engineer can include a resistance, called a *dirt*, *scale*, or *fouling factor*, when he determines an over-all coefficient of heat transfer. Equation (12) illustrates the method for handling the fouling factor. In this case, the fouling coefficients h'_d and h''_d are used to account for scale or dirt formation on the heat-transfer surfaces.

Fouling factors, equivalent to $1/h_d$, are often presented in the literature for various materials and conditions. Values of h_d for common process services are listed in Table 3. Because the scale or dirt resistance increases with the time the equipment is in service, some basis must be chosen for numerical values of fouling factors. The common basis is a time period of 1 year, and this condition applies to the values of h_d presented in Table 3. When the correct fouling factors are used, the equipment should be capable of transferring more than the required amount of heat when the equipment is clean. At the end of approximately 1 year of service, the capacity will have decreased to the design value, and a shutdown for cleaning will be necessary. With this approach, numerous shutdowns for cleaning individual units are not necessary. Instead, annual or periodic shutdowns of the entire plant can be scheduled, at which time all heat-transfer equipment can be cleaned and brought up to full capacity.

Mean Area of Heat Transfer

The cross-sectional area of heat transfer A in Eq. (1) can vary appreciably along the length of the heat-transfer path x. Therefore, the shape of the solid through which heat is flowing must be known before Eq. (1) can be integrated to give Eq. (2). The exact value for A_m, based on the limiting areas A_1 and A_2, follows for three cases commonly encountered in heat-transfer calculations:

1. Conduction of heat through solid of constant cross section (example, a large flat plate)

$$A_m = A_{\text{arith. avg.}} = \frac{A_1 + A_2}{2} \tag{13}$$

2. Conduction of heat through a solid when the cross-sectional area of heat transfer is proportional to the radius (example, a long hollow cylinder)

$$A_m = A_{\text{log mean}} = \frac{A_1 - A_2}{\ln (A_1/A_2)} \tag{14}$$

3. Conduction of heat through a solid when the cross-sectional area of heat transfer is proportional to the square of the radius (example, a hollow sphere)

$$A_m = A_{\text{geom. mean}} = \sqrt{A_1 A_2} \tag{15}$$

When the value of A_1/A_2 (or A_2/A_1 if A_2 is larger than A_1) does not exceed 2.0, the mean area based on an arithmetic-average value is within 4 per cent of the logarithmic-mean area and within 6 per cent of the geometric-mean area. This accuracy is considered adequate for most design calculations. It should be noted that the arithmetic-average value is always greater than the logarithmic mean or the geometric mean.

Mean Temperature-difference Driving Force

When a heat exchanger is operated continuously, the temperature difference between the hot and cold fluids usually varies throughout the length of the exchanger. To account for this condition, Eqs. (4) and (11) can be expressed in a differential form as

$$dq = h\, dA\, \Delta t_f \tag{16}$$

$$dq = U\, dA\, \Delta t_{oa} \tag{17}$$

The variations in Δt and the heat-transfer coefficients must be taken into account when Eqs. (16) and (17) are integrated. Under some conditions, a graphical or stepwise integration may be necessary, but algebraic solutions are possible for many of the situations commonly encountered with heat-transfer equipment.

Constant Heat-transfer Coefficient. The integrated forms of Eqs. (16) and (17) are often expressed in the following simplified forms:

$$q = hA\, \Delta t_{f_m} \tag{18}$$

$$q = UA\, \Delta t_{oa_m} \tag{19}$$

where the subscript m refers to a mean value. Under the following conditions, the correct mean temperature difference is the logarithmic-mean value:

1. U (or h) is constant.
2. Mass flow rate is constant.
3. There is no partial phase change.
4. Specific heats of the fluids remain constant.

5. Heat losses are negligible.

6. Equipment is for counterflow, parallel flow, or any type of flow if the temperature of one of the fluids remains constant (phase change can occur) over the entire heat-transfer area.

$$\Delta t_{oam} = \Delta t_{oa\,\text{log mean}} = \frac{\Delta t_{oa_1} - \Delta t_{oa_2}}{\ln (\Delta t_{oa_1}/\Delta t_{oa_2})} \tag{20}$$

where Δt_{oa_1} and Δt_{oa_2} represent the two terminal values of the over-all temperature-difference driving force. For design calculations, an arithmetic-average temperature difference can be used in place of the logarithmic-mean value if the ratio $\Delta t_{oa_1}/\Delta t_{oa_2}$ (or $\Delta t_{oa_2}/\Delta t_{oa_1}$ if Δt_{oa_2} is greater than Δt_{oa_1}) does not exceed 2.0.

When multipass exchangers are involved and the first five conditions listed in the preceding paragraph apply, values for Δt_{oa_m} can be obtained by integrating Eq. (17) or, more simply, from plots that give the correct Δt_{oa_m} for various types of multipass exchangers as a function of the logarithmic-mean temperature difference for counterflow.*†‡ Figure 15-2 is

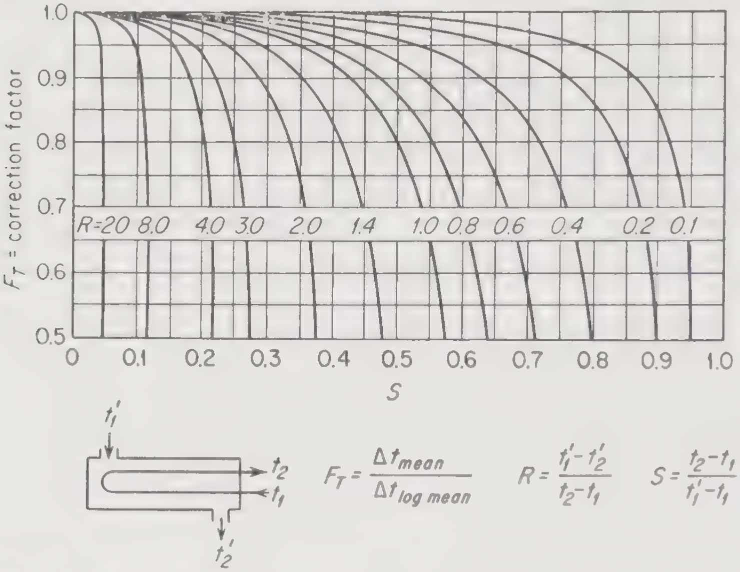

Fig. 15-2. Chart for determining correct, mean temperature-difference driving force for an exchanger with one shell pass and two or more even-numbered tube passes. (Correction factor F_T is based on the $\Delta_{\text{log mean}}$ for counterflow. If F_T is below 0.7, operation of the exchanger may not be practical.)

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* J. H. Perry, "Chemical Engineers' Handbook," 3d ed., McGraw-Hill Book Company, Inc., New York, 1950.

† "Standards of Tubular Exchanger Manufacturers Association," 3d ed., New York, 1952.

‡ These plots present graphically the results of integrating Eq. (17).

a plot of this type for the common case of an exchanger with one shell pass and two or more even-numbered tube passes.

Variable Heat-transfer Coefficient. If the heat-transfer coefficient varies with temperature, one can assume that the complete exchanger consists of a number of smaller exchangers in series and that the coefficient varies linearly with temperature in each of these sections. When the last five conditions listed in the preceding section hold and the over-all coefficient varies linearly with temperature, integration of Eq. (17) gives

$$q = A\frac{U_1\,\Delta t_{oa_2} - U_2\,\Delta t_{oa_1}}{\ln\,(U_1\,\Delta t_{oa_2}/U_2\,\Delta t_{oa_1})} \tag{21}$$

The values of q and A in Eq. (21) apply to the section of the equipment between the limits indicated by the subscripts 1 and 2. Consequently, the total value of q or A for the entire exchanger can be obtained by summing the quantities for each of the individual sections.

Unsteady-state Heat Transfer

When heat is conducted through a solid under unsteady-state conditions, the following general equation applies:

$$\frac{\partial t}{\partial \theta} = \frac{1}{\rho c_p}\left[\frac{\partial}{\partial x}\left(k_x\frac{\partial t}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y\frac{\partial t}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z\frac{\partial t}{\partial z}\right)\right] \tag{22}$$

where c_p is the heat capacity of the material through which heat is being conducted and x, y, and z represent the cartesian coordinates. The solution of any problem involving unsteady-state conduction consists essentially in integrating Eq. (22) with the proper boundary conditions.

For a homogeneous and isotropic material, Eq. (22) becomes

$$\frac{\partial t}{\partial \theta} = \alpha\left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2}\right) \tag{23}$$

where α = thermal diffusivity = $k/\rho c_p$, ft^2/hr.

Many cases of practical interest in unsteady-state heat transfer involve one-dimensional conduction. For one-dimensional conduction in the x direction, Eq. (23) reduces to

$$\frac{\partial t}{\partial \theta} = \alpha\frac{\partial^2 t}{\partial x^2} \tag{24}$$

Solutions of Eqs. (23) and (24) for various shapes and boundary conditions are available in the literature. The simplest types of problems are those in which the surface of a solid suddenly attains a new temperature and this temperature remains constant. Such a condition can exist only if the temperature of the surroundings remains constant and there is no resistance to heat transfer between the surface and the surroundings (i.e., surface film coefficient is infinite). Although there are few practical cases when these conditions occur, the solutions of such problems are of interest to the design engineer because they indicate the results obtainable for the limiting condition of the maximum rate of unsteady-state heat transfer.

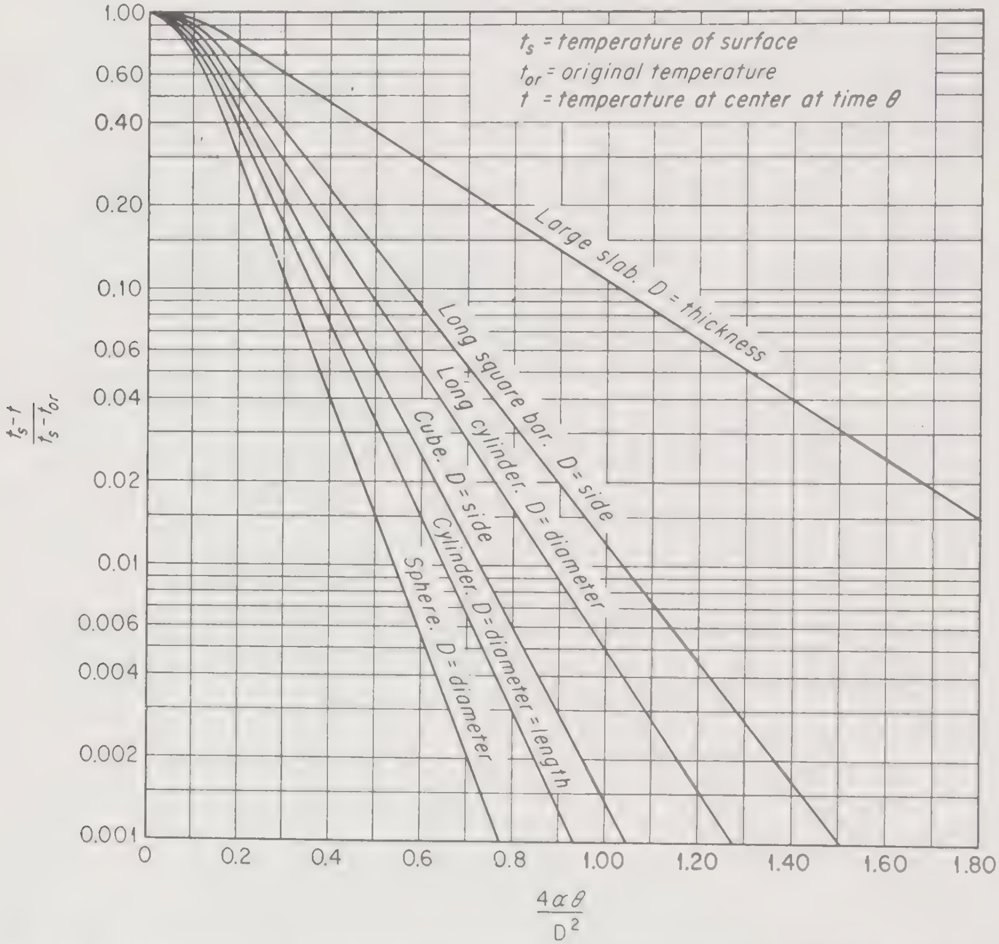

FIG. 15-3. Mid-point or mid-plane temperatures for unsteady-state heating or cooling of solids having negligible surface resistance.

Figure 15-3 presents graphically the results of integrating the unsteady-state equations for a sudden change from a uniform surface and bulk temperature to a new constant surface temperature when the surface film coefficient is infinite.* The reference temperature in this plot is at the center point, center line, or center plane, and results are presented for a slab, a square bar, a cube, a cylinder, and a sphere.

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* E. D. Williamson and L. H. Adams, *Phys. Rev.*, **14**:99 (1919).

Example 2. Estimation of Minimum Time Required for Unsteady-state Cooling. A solid steel cylinder has a diameter of 3 ft and a length of 3 ft. The temperature of the cylinder is 1000°F. It is suddenly placed in a well-ventilated room where the temperature of the room remains constant at 90°F. Estimate the minimum time (i.e., surface film coefficient is infinite) the cylinder must remain in the room before the temperature at the center can drop to 150°F. Assume the following values for the steel: $k = 24.0$ Btu/(hr)(sq ft)(°F/ft); $c_p = 0.12$ Btu/(lb)(°F); $\rho = 488$ lb/cu ft.

Solution

$\alpha = k/\rho c_p = 24/(488)(0.12) = 0.41\ \text{ft}^2/\text{hr}$

$t_s = 90°\text{F}$

$t = 150°\text{F}$

$t_{or} = 1000°\text{F}$

$$\frac{t_s - t}{t_s - t_{or}} = \frac{-60}{-910} = 0.066$$

From Fig. 15-3,

$$\frac{4\alpha\theta}{D^2} = 0.42$$

$$\theta = \frac{(0.42)(3)^2}{(4)(0.41)} = 2.3\ \text{hr}$$

The minimum time before temperature at center of cylinder can drop to 150°F = 2.3 hr.

Determination of Heat-transfer Coefficients

Exact values of convection heat-transfer coefficients for a given situation can be obtained only by experimental measurements under the particular operating conditions. Approximate values, however, can be obtained for use in design by employing correlations based on general experimental data. A number of correlations that are particularly useful in design work are presented in the following sections. In general, the relationships applicable to turbulent conditions are more accurate than those for viscous conditions. Film coefficients obtained from the correct use of equations in the turbulent-flow range will ordinarily be within ±20 per cent of the true experimental value, but values determined for viscous-flow conditions or for condensation, boiling, natural convection, and shell sides of heat exchangers may be in error by more than 100 per cent. Because of the inherent inaccuracies in the methods for estimating film coefficients, some design engineers prefer to use over-all coefficients based on past experience, while others include a large safety factor in the form of fouling factors or fouling coefficients.

Film Coefficients for Fluids in Pipes and Tubes (No Change in Phase). The following equations are based on the correlations presented by Sieder and Tate: *

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* E. N. Sieder and G. E. Tate, *Ind. Eng. Chem.*, **28**:1429 (1936).

For viscous flow ($DG/\mu < 2100$),

$$\frac{h_iD}{k} = 1.86\left(\frac{DG}{\mu}\frac{c_p\mu}{k}\frac{D}{L}\right)^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14} = 1.86\left(\frac{4wc_p}{\pi kL}\right)^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{25}$$

For turbulent flow above the transition region ($DG/\mu > 10{,}000$),

$$\frac{h_iD}{k} = 0.023\left(\frac{DG}{\mu}\right)^{0.8}\left(\frac{c_p\mu}{k}\right)^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{26}$$ *

For transition region ($DG/\mu = 2100$ to $10{,}000$), see Fig. 15-4,

where D = diameter of pipe or tube (inside), ft
G = mass velocity inside tube, lb/(hr)(sq ft of cross-sectional area)
c_p = heat capacity of fluid at constant pressure, Btu/(lb)(°F)
μ = viscosity of fluid (subscript w indicates evaluation at wall temperature), lb/(hr)(ft)
L = heated length of straight tube, ft
w = weight rate of flow per tube, lb/hr
k, μ, and c_p are evaluated at the average bulk temperature of the fluid

Equations (25) and (26) are applicable for organic fluids, aqueous solutions, water, and gases. The two equations are plotted in Fig. 15-4 to

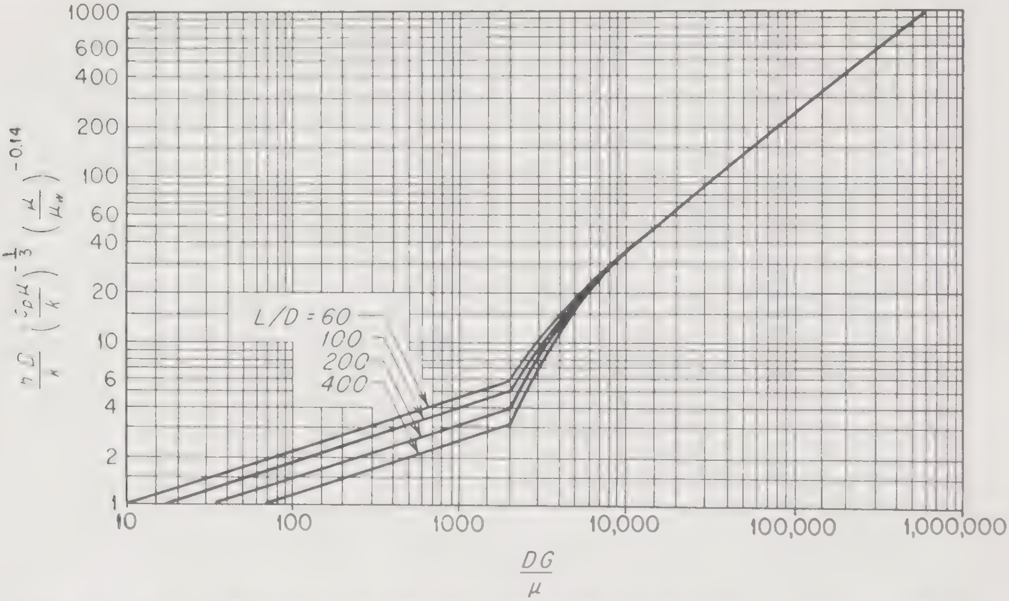

FIG. 15-4. Plot for estimating film coefficients for fluids flowing in pipes and tubes. [Based on Eqs. (25) and (26).]

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* In some references, the constant 0.027 is used in place of 0.023. The constant 0.023 is recommended in order to make Eq. (26) generally applicable for water, organic fluids, and gases at moderate Δt.

facilitate their solution and to indicate the values for use in the transition region.

Simplified Equations. For common gases, Eq. (26) can be simplified to give the following approximate equation: *

$$h_i = \frac{0.014 c_p G^{0.8}}{D^{0.2}} \tag{27}$$

Similarly, for water at ordinary temperatures and pressures,

$$h_i = \frac{150(1 + 0.011 t_b)(V')^{0.8}}{(D')^{0.2}} \tag{28}$$

Equations (27) and (28) are dimensional, and a value of h_i as Btu (hr)(sq ft)(°F) is obtained only if the following units are employed for the indicated variables:

c_p = heat capacity of fluid, Btu/(lb)(°F)
D = diameter, ft
D' = diameter, in.
G = mass velocity inside tube, lb/(hr)(sq ft)
t_b = average (i.e., bulk) temperature of water, °F
V' = velocity of water, fps

Noncircular Cross Section—Equivalent Diameter. The situation is often encountered in which a fluid flows through a conduit having a noncircular cross section, such as an annulus. The heat-transfer coefficients for turbulent flow can be determined by using the same equations that apply to pipes and tubes if the pipe diameter D appearing in these equations is replaced by an equivalent diameter D_e. Best results are obtained if this equivalent diameter is taken as four times the hydraulic radius, where the hydraulic radius is defined as the cross-sectional flow area divided by the *heated* perimeter. For example, if heat is being transferred from a fluid in a center pipe to a fluid flowing through an annulus, the film coefficient around the inner pipe would be based on the following equivalent diameter:

$$D_e = 4 \times \text{hydraulic radius} = 4 \times \frac{\pi D_2^2/4 - \pi D_1^2/4}{\pi D_1} = \frac{D_2^2 - D_1^2}{D_1}$$

where D_1 and D_2 represent, respectively, the inner and outer diameters of the annulus.

The difference between the hydraulic radii for heat transfer and for fluid flow should be noted. In the preceding example, the correct equivalent diameter for evaluating friction due to the fluid flow in the annulus

* Equations (27) and (28) are derived by neglecting the viscosity correction factor in Eq. (26) and substituting average values for the physical properties. For more details and other simplified equations, see W. H. McAdams, "Heat Transmission," 3d ed., McGraw-Hill Book Company, Inc., New York, 1954.

would be four times the cross-sectional flow area divided by the *wetted* perimeter, or $4 \times \dfrac{\pi D_2^2/4 - \pi D_1^2/4}{\pi D_2 + \pi D_1} = D_2 - D_1$.

Film Coefficients for Fluids Flowing outside Pipes and Tubes (No Change in Phase). In the common types of baffled shell-and-tube exchangers, the shell-side fluid flows across the tubes. The equations for predicting heat-transfer coefficients under these conditions are not the same as those for flow of fluids inside pipes and tubes. An approximate value for shell-side coefficients in a cross-flow exchanger with segmental baffles and reasonable clearance between baffles, between tubes, and between baffles and shell can be obtained by using the following correlation: *

$$\frac{h_o D_o}{k_f} = \frac{a_o}{F_s}\left(\frac{D_o G_s}{\mu_f}\right)^{0.6}\left(\frac{c_p \mu}{k}\right)_f^{1/3} \tag{29}$$

where a_o = 0.33 if tubes in tube bank are staggered and 0.26 if tubes are in line

F_s = safety factor to account for bypassing effects †

G_s = shell-side mass velocity across tubes, based on minimum free area between baffles at shell axis,‡ lb/(hr)(sq ft)

Subscript f refers to properties at average film temperature

Equation (29) can be used to obtain approximate film coefficients for hydrocarbons, aqueous solutions, water, and gases when the Reynolds number $(D_o G_s/\mu_f)$ is in the ordinary range of 2000 to 32,000.

Film Coefficients and Over-all Coefficients for Miscellaneous Cases. Table 4 presents equations for use in the estimation of heat-transfer film coefficients for condensation, boiling, and natural convection. Values showing the general range of film coefficients for various situations are indicated in Table 5.

The design engineer often prefers to use over-all coefficients directly without attempting to evaluate individual film coefficients. When this is

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* A. P. Colburn, *Trans. AIChE*, **29**:174 (1933).

† Amount of shell-side bypassing between the cross baffles and the shell, between tubes and tube holes in baffles, and between outermost tubes and shell depends on the manufacturing methods and tolerances for the exchanger. The amount of bypassing can have a large influence on the shell-side heat-transfer coefficient. The value of F_s is usually between 1.0 and 1.8, and a value of 1.6 is often recommended.

‡ The free area for use in Eqs. (29) and (31) occurs where the total cross-sectional area of the shell (normal to direction of flow) is a maximum, and the free area at this axis plane is based on the transverse or diagonal openings that give the smallest free area. The free area S_o for use in evaluating G_s for the common case of a full-packed shell and transverse openings giving the smallest free area can be estimated to be

$$\frac{(\text{ID of shell})(\text{clearance between adjacent tubes})(\text{baffle spacing})}{\text{center-to-center distance between adjacent tubes}}$$

TABLE 4. EQUATIONS AND METHODS FOR ESTIMATING FILM COEFFICIENTS OF HEAT TRANSFER FOR COMMON CASES

Type of heat transfer	Limitations
Film-type condensation of vapors:	
Outside horizontal tubes $h = 0.725 \left(\frac{k_f^3 \rho_f^2 g \lambda_c}{N_V D_o \mu_f \, \Delta t_f} \right)^{1/4} = 0.95 \left(\frac{k_f^3 \rho_f^2 g L}{w \mu_f} \right)^{1/3}$ For steam, average h at 1 atm pressure $= \frac{3100}{(N_V D_o)^{1/4} (\Delta t_f)^{1/3}}$ See Fig. 15-5, which shows the effect of noncondensable gases	McAdams * Pure saturated vapors $\frac{2w}{L\mu_f} < 2000$ Physical properties are for condensate
Vertical tubes $h = 1.47 \left(\frac{\pi D_o k_f^3 \rho_f^2 g}{4 w \mu_f} \right)^{1/3}$ For steam, average h at 1 atm pressure $= \frac{4000}{L^{1/4} (\Delta t_f)^{1/3}}$	McAdams * Pure saturated vapors $\frac{4w}{\pi D_o \mu_f} < 2000$ Physical properties are for condensate
Boiling liquids outside horizontal tubes:	
Film boiling (above critical Δt_f) $h_{co} = 0.62 \left[\frac{k_v^3 \rho_v (\rho_L - \rho_v) g \lambda_c}{D_o \mu_v \, \Delta t_f} \right]^{1/4}$	Bromley † For saturated liquids on submerged surfaces; film coefficient h_{co} is for conduction through the vapor; no radiation effect is included
Nucleate boiling (below critical Δt_f) Value of h depends on Δt_f, type of surface, and materials involved (critical Δt_f for water as temperature drop from heating surface to liquid is approximately 45°F)	
Natural convection:	
General equation $\frac{h_c L}{k_f} = c_c [(N_{\mathrm{Gr}})_f (N_{\mathrm{Pr}})_f]^n$	McAdams * Values of c_c and n depend on $N_{\mathrm{Gr}} \times N_{\mathrm{Pr}}$ and the geometry of the surfaces

TABLE 4. EQUATIONS AND METHODS FOR ESTIMATING FILM COEFFICIENTS OF HEAT TRANSFER FOR COMMON CASES (*Continued*)

Type of heat transfer		Limitations
Simplified equations for air $h_c = K(\Delta t)^{0.25}$		Kern ‡ Ordinary air temperature, atmospheric pressure, normal conditions; for more exact equations, see McAdams *
Physical arrangement of equipment	K	
Horizontal plates facing upward.....	0.38	
Horizontal plates facing downward...	0.20	
Vertical plates more than 2 ft high...	0.30	
Vertical plates less than 2 ft high....	$\dfrac{0.28}{(\text{vertical height, ft})^{0.25}}$	
Vertical pipes more than 1 ft high....	$\dfrac{0.22}{(D_o, \text{ ft})^{0.25}}$	
Horizontal pipes..................	$\dfrac{0.27}{(D_o, \text{ ft})^{0.25}}$	

λ_c = lambda, latent heat of condensation, Btu/lb

g = local gravitational acceleration, ft/(hr)(hr)

N_V = number of rows of tubes in a vertical tier

D_o = outside diameter of tube, ft

Δt_f = temperature-difference driving force across film, °F

L = heated length of straight tube or length of heat-transfer surface, ft

w = weight rate of flow of condensate per tube from lowest point on condensing surface, lb/(hr)(tube)

$(N_{Gr})_f$ = Grashof number = $\dfrac{L^3 \rho_f^2 g \beta_f \, \Delta t_f}{\mu_f^2}$

$(N_{Pr})_f$ = Prandtl number = $\left(\dfrac{c_p \mu}{k}\right)_f$

β = beta, coefficient of volumetric expansion, 1/°F

c_c, K, n = constants

Subscript f designates "at average film temperature"

Subscript v designates vapor at average vapor temperature

Subscript L designates liquid at average liquid temperature

* W. H. McAdams, "Heat Transmission," 3d ed., McGraw-Hill Book Company, Inc., New York, 1954.

† L. A. Bromley, *Chem. Eng. Progr.*, **46**:221 (1950).

‡ D. Q. Kern, "Process Heat Transfer," McGraw-Hill Book Company, Inc., New York, 1950.

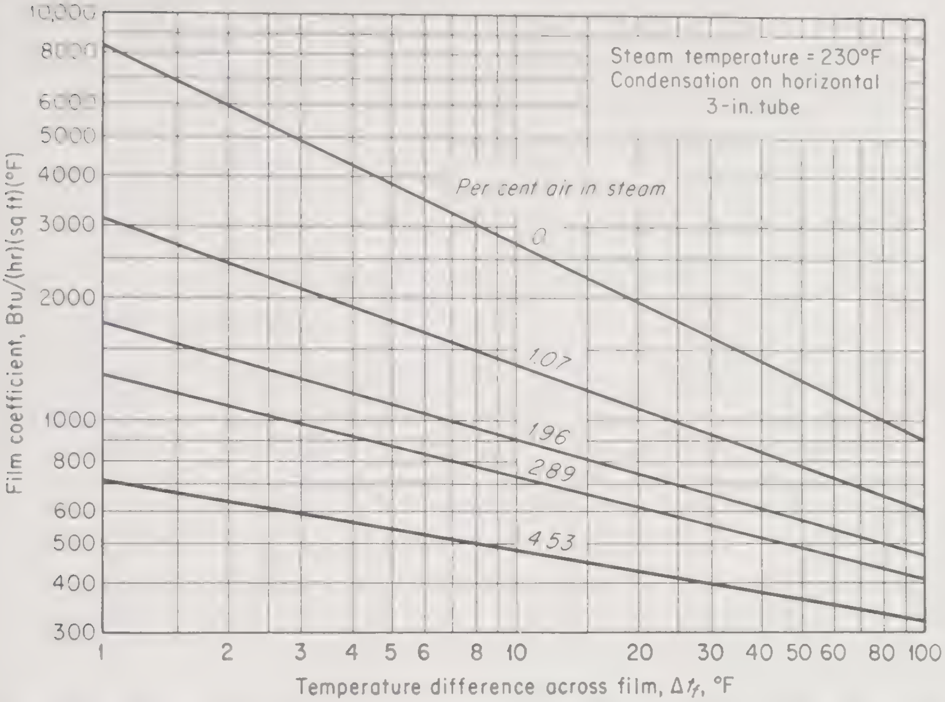

Fig. 15-5. Film coefficients for condensing steam. [*D. F. Othmer, Ind. Eng. Chem.*, **21**:576 (1929).]

the case, the engineer must predict an over-all coefficient on the basis of past experience with equipment and materials similar to those involved in the present problem. Design values of over-all heat-transfer coefficients for many of the situations commonly encountered by design engineers are listed in Table 6.

Table 5. Order of Magnitude of Individual Film Coefficients

Condition	*h, Btu/(hr)(sq ft)(°F)*
Dropwise condensation of steam	10,000–20,000
Film-type condensation of steam	1,000–3,000
Boiling water	300–9,000
Film-type condensation of organic vapors	200–400
Heating or cooling of water	50–3,000
Heating or cooling of organic solvents	30–500
Heating or cooling of oils	10–120
Superheated steam	5–30
Heating or cooling of air	0.2–20

TABLE 6. APPROXIMATE DESIGN VALUES OF OVER-ALL HEAT-TRANSFER COEFFICIENTS *

The following values of over-all heat-transfer coefficients are based primarily on results obtained in ordinary engineering practice. The values are approximate because variation in fluid velocities, amount of noncondensable gases, viscosities, cleanliness of heat-transfer surfaces, type of baffles, operating pressure, and similar factors can have a significant effect on the over-all heat-transfer coefficients. The values are useful for preliminary design estimates or for rough checks on heat-transfer calculations.

Upper range of over-all coefficients given for coolers may also be used for condensers. Upper range of over-all coefficients given for heaters may also be used for evaporators.

Units of coefficients are Btu/(hr)(sq ft)(°F).

Hot fluid	Cold fluid	Fouling coefficient h_d	Over-all coefficient U_d
	Coolers		
Water	Water	1000	250–500
Methanol	Water	1000	250–500
Ammonia	Water	1000	250–500
Aqueous solutions	Water	1000	250–500
Light organics—viscosities less than 0.5 cp (benzene, toluene, acetone, ethanol, gasoline, light kerosene, and naphtha)	Water	300	75–150
Medium organics—viscosities between 0.5 and 1.0 cp (kerosene, straw oil, hot gas oil, hot absorber oil, some crude oils)	Water	300	50–125
Heavy organics—viscosities greater than 1.0 cp (cold gas oil, lube oils, fuel oils, reduced crude oil, tars, and asphalts)	Water	300	5–75
Gases	Water	300	2–50
Water	Brine	300	100–200
Light organics	Brine	300	40–100
	Heaters		
Steam	Water	1000	200–700
Steam	Methanol	1000	200–700
Steam	Ammonia	1000	200–700
Steam	Aqueous solutions:		
	Less than 2.0 cp	1000	200–700
	More than 2.0 cp	1000	100–500
Steam	Light organics	300	100–200
Steam	Medium organics	300	50–100
Steam	Heavy organics	300	6–60
Steam	Gases	300	5–50
Dowtherm	Gases	300	4–40
Dowtherm	Heavy organics	300	6–60

Table 6. Approximate Design Values of Over-all Heat-transfer Coefficients *
(*Continued*)

Hot fluid	Cold fluid	Fouling coefficient h_d	Over-all coefficient U_d
Exchangers (No Phase Change)			
Water	Water	1000	250–500
Aqueous solutions	Aqueous solutions	1000	250–500
Light organics	Light organics	300	40–75
Medium organics	Medium organics	300	20–60
Heavy organics	Heavy organics	300	10–40
Heavy organics	Light organics	300	30–60
Light organics	Heavy organics	300	10–40

* D. Q. Kern, "Process Heat Transfer," McGraw-Hill Book Company, Inc., New York, 1950.

PRESSURE DROP IN HEAT EXCHANGERS

The major cause of pressure drop in heat exchangers is friction resulting from flow of fluids through the exchanger tubes and shell. Friction due to sudden expansion, sudden contraction, or reversal in direction of flow also causes a pressure drop. Changes in vertical head and kinetic energy can influence the pressure drop, but these two effects are ordinarily relatively small and can be neglected in many design calculations.

Tube-side Pressure Drop. It is convenient to express the pressure drop for heat exchangers in a form similar to the Fanning equation as presented in Chap. 14. Because the transfer of heat is involved, a factor must be included for the effect of temperature change on the friction factor. Under these conditions, the pressure drop through the tube passes (i.e., tube side) of a heat exchanger may be expressed as follows (subscript i refers to inside of tubes at bulk temperature):

$$-\Delta P_i = \frac{B_i 2 \mathfrak{f}_i G^2 L n_p}{g_c \rho_i D_i \phi_i} \tag{30}$$

where $\mathfrak{f}_i$ = Fanning friction factor for isothermal flow based on conditions at the arithmetic-average temperature of the fluid; $\mathfrak{f}_i$ as function of D_iG/μ_i is shown in Fig. 14-1

n_p = number of tube passes

g_c = conversion factor in Newton's law of motion, $(32.17)(3600)^2$ ft-lb mass/(hr)(hr)(lb force)

ϕ_i = correction factor for nonisothermal flow = $1.1(\mu_i/\mu_w)^{0.25}$ when D_iG/μ_i is less than 2100 and $1.02(\mu_i/\mu_w)^{0.14}$ when D_iG/μ_i is greater than 2100; μ_i is viscosity at arithmetic-average (bulk) temperature of fluid, and μ_w is viscosity of fluid at average temperature of the inside-tube wall surface

B_i = correction factor to account for friction due to sudden contraction, sudden expansion, and reversal of flow direction

$= 1 + (F_e + F_c + F_r)/(2\mathfrak{f}_iG^2L/g_c\rho_i^2D_i\phi_i)$ *

Shell-side Pressure Drop. The pressure drop due to friction when a fluid is flowing parallel to and outside of tubes can be calculated in the normal manner described in Chap. 14 by using a mean diameter equal to four times the hydraulic radius of the system and by including all frictional effects due to contraction and expansion. In heat exchangers, however, the fluid flow on the shell side is usually across the tubes, and many types and arrangements of baffles may be used. As a result, no single explicit equation can be given for evaluating pressure drop on the shell side of all heat exchangers.

For the case of flow across tubes, the following equation can be used to approximate the pressure drop due to friction (subscript o refers to outside of tubes at bulk temperature):

$$-\Delta P_o = \frac{B_o 2\mathfrak{f}' N_r G_s^2}{g_c\rho_o} \tag{31}$$

where $\mathfrak{f}'$ = special friction factor for shell-side flow

N_r = number of rows of tubes across which shell fluid flows

B_o = correction factor to account for friction due to reversal in direction of flow, recrossing of tubes, and variation in cross section;

---

* F_e (friction due to sudden enlargement) and F_c (friction due to sudden contraction) can be estimated by the methods indicated in Chap. 14. $F_e = (V_i - V_{\text{header}})^2/2g_c$. $F_c = K_cV_i^2/2g_c$. F_r (friction due to reversal of flow direction) depends on the details of the exchanger construction, but a good estimate for design work is $(0.5V_i^2/2g_c) \times (n_p - 1)/n_p$. Designating S_i/S_H as the ratio of total inside-tube cross-sectional area per pass to header cross-sectional area per pass and K_1 as $[1 - (S_i/S_H)]^2 + K_c + 0.5 \times (n_p - 1)/n_p$,

$$B_i = 1 + \frac{K_1D_i\phi_i}{4\mathfrak{f}_iL}$$

If the flow is highly turbulent and in smooth tubes, $\mathfrak{f}_i$ may be taken as $0.046(D_iG/\mu_i)^{-0.2}$. Combining the preceding relationships with Eqs. (4), (11), (26), and the rate equation for no phase change [Eq. (36)] gives, for smooth tubes and turbulent flow,

$$B_i = 1 + \frac{0.51K_1n_p\,\Delta t_{f_1}\,(\mu_i/\mu_w)^{0.28}}{(t_2 - t_1)_i(c_p\mu/k)_i^{2/3}}$$

where $t_2 - t_1$ represents the total change in temperature of the fluid as it flows through the exchanger tubes.

when the flow is across unbaffled tubes, B_o can be taken as 1.0; as a rough approximation, B_o can be estimated as equal to the number of tube crosses

The friction factor f' is a function of the Reynolds number of the flowing fluid and the arrangement of the tubes. For the common case of D_oG_s/μ_f in the range of 2000 to 40,000, the friction factor in Eq. (31) may be represented as

$$f' = b_o\left(\frac{D_oG_s}{\mu_f}\right)^{-0.15} \tag{32}$$

The following approximate equations for b_o are based on the data of Grimson:*†

For staggered tubes,

$$b_o = 0.23 + \frac{0.11}{(x_T - 1)^{1.08}} \tag{33}$$

For tubes in line,

$$b_o = 0.044 + \frac{0.08x_L}{(x_T - 1)^{0.43+1.13/x_L}} \tag{34}$$

where x_T = ratio of pitch (i.e., tube center-to-center distance) transverse to flow to tube diameter, dimensionless; and x_L = ratio of pitch parallel to flow to tube diameter, dimensionless.

Example 3. Estimation of Film Coefficient and Pressure Drop inside Tubes in a Shell-and-Tube Exchanger. A horizontal shell-and-tube heat exchanger with two tube passes and one shell pass is being used to heat 70,000 lb/hr of 100 per cent ethanol from 60 to 140°F at atmospheric pressure. The ethanol passes through the inside of the tubes, and saturated steam at 230°F condenses on the shell side of the tubes. The tubes are steel with an OD of ¾ in. and a BWG of 14. The exchanger contains a total of 100 tubes (50 tubes per pass), and the average number of tubes in a vertical tier can be taken as 6. The ratio of total inside-tube cross-sectional area per pass to header cross-sectional area per pass can be assumed to be 0.5. Estimate the film coefficient for the ethanol and the pressure drop due to friction through the tube side of the exchanger.

Solution

From the Appendix,
Tube wall thickness = 0.083 in.
Tube ID = 0.584 in.
Tube OD = 0.75 in.
Flow area per tube = 0.268 sq in.

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* E. D. Grimson, *Trans. ASME*, **59**:583 (1937), **60**:381 (1938).

M. Jacob, *Trans. ASME*, **60**:384 (1938).

W. H. McAdams, "Heat Transmission," 3d ed., McGraw-Hill Book Company, Inc., New York, 1954.

† In Eqs. (33) and (34), best results are obtained if x_T is between 1.5 and 4.0. For design purposes, the range can be extended down to 1.25. When the Reynolds number is between 2000 and 10,000 with tubes in line, f' for a given tube spacing can be assumed to be constant at the value obtained when the Reynolds number is 10,000.

Inside surface area per lin ft = 0.1529 sq ft
k for steel = 26 Btu/(hr)(sq ft)(°F/ft)
At $(60 + 140)/2 = 100$°F,
μ for ethanol = 0.9 centipoise
k for ethanol = 0.094 Btu/(hr)(sq ft)(°F/ft)
c_p for ethanol = 0.62 Btu/(lb)(°F)
ρ for ethanol = 49 lb/cu ft

$$\text{Mass velocity} = G = \frac{(70{,}000)(144)}{(0.268)(50)} = 752{,}000 \text{ lb/(hr)(sq ft)}$$

$$N_{\text{Re}} = \frac{DG}{\mu} = \frac{(0.584)(752{,}000)}{(12)(0.9)(2.42)} = 16{,}800$$

$$\frac{c_p\mu}{k} = \frac{(0.62)(0.9)(2.42)}{0.094} = 14.4$$

Equation (26), for the evaluation of the average coefficient, applies under these conditions. The only remaining unknown in the equation is μ_w.

Evaluation of μ_w. As a first approximation, assume the following:
Δt over ethanol film = 70% of average total $\Delta t = 0.70(230 - 100) = 91$°F
Δt over steam film = 8% of average total $\Delta t = 0.08(230 - 100) = 10$°F
Wall temperature for evaluation of $\mu_w = 100 + 91 = 191$°F
$\mu_w = \mu$ of ethanol at 191°F = 0.4 centipoise
$\mu/\mu_w = 0.9/0.4 = 2.25$
From Eq. (26),

$$h_i = \frac{k}{D}(0.023)\left(\frac{DG}{\mu}\right)^{0.8}\left(\frac{c_p\mu}{k}\right)^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14}$$

$$= \frac{(0.094)(12)(0.023)(16{,}800)^{0.8}(14.4)^{1/3}(2.25)^{0.14}}{0.584}$$

$$= 290 \text{ Btu/(hr)(sq ft)(°F)}$$

Check on Δt assumptions. From Table 3, a fouling coefficient of 1000 Btu/(hr)(sq ft)(°F) is adequate for the ethanol. No fouling coefficient will be used for the steam.

From Table 4, the steam film coefficient can be approximated as

$$\frac{3100}{[(6)(0.75/12)]^{1/4}(10)^{1/3}} = 1800 \text{ Btu/(hr)(sq ft)(°F)}$$

By Eq. (12) (basing U_d on the inside tube area),

$$\frac{1}{U_d} = \frac{1}{h'A'_f} + \frac{A}{h''A''_f} + \frac{Ax_w}{kA_w} + \frac{A}{h'_dA'_f};$$

$$= \frac{1}{290} + \frac{0.584}{(1800)(0.75)} + \frac{(0.584)(0.083)}{(26)(0.667)(12)} + \frac{1}{1000}$$

$$= 0.00345 + 0.00043 + 0.00023 + 0.001 = 0.00511$$

$$\text{Per cent } \Delta t \text{ over ethanol film} = \frac{0.00345}{0.00511}(100) = 68\% \text{ of total } \Delta t$$

$$\text{Per cent } \Delta t \text{ over steam film} = \frac{0.00043}{0.00511}(100) = 8.4\% \text{ of total } \Delta t$$

The Δt assumptions are adequate.

Determination of pressure drop due to friction. Assume U_d is constant over length of exchanger:

$$U_d = \frac{1}{0.00511} = 196 \text{ Btu/(hr)(sq ft of inside area)(°F)}$$

$$\Delta t_{oa,m} = \frac{(230 - 60) + (230 - 140)}{2} = 130°\text{F} = \Delta t_{oa,\text{arith avg}}$$

The arithmetic-average value is satisfactory because the temperature of the steam remains constant and the ratio $\Delta t_1/\Delta t_2$ is less than 2.0.

$$q = (70{,}000)(0.62)(140 - 60) = 3{,}470{,}000 \text{ Btu/hr}$$

By Eq. (19),

$$A = \frac{q}{U_d\,\Delta t_{oa,m}} = \frac{3{,}470{,}000}{(196)(130)} = 136 \text{ sq ft of inside tube area}$$

$$\text{Length per tube} = L = \frac{136}{(0.1529)(100)} = 8.9 \text{ ft}$$

By Eq. (30),

$$-\Delta P_i = \frac{B_i 2\mathfrak{f}_i G_i^2 L n_p}{g_c \rho_i D_i \phi_i}$$

$$B_i = 1 + \frac{F_e + F_c + F_r}{2\mathfrak{f}_i G_i^2 L/g_c \rho_i^2 D_i \phi_i} = 1 + \frac{0.51 K_1 n_p\,\Delta t_{f1}\,(\mu_i/\mu_w)^{0.28}}{(t_2 - t_1)_i (c_p\mu/k)_i^{2/3}}$$

$$K_1 = \left(1 - \frac{S_i}{S_H}\right)^2 + K_c + \frac{0.5(n_p - 1)}{n_p}$$

$$= (1 - 0.5)^2 + 0.3 + (0.5)(1)(\tfrac{1}{2}) = 0.8$$

$$K_c \text{ (Chap. 14, Table 1)} = (0.4)(1.25 - 0.5) = 0.3$$

$$B_i = 1 + \frac{(0.51)(0.8)(2)(0.68)(230 - 100)(2.25)^{0.28}}{(140 - 60)(14.4)^{2/3}} = 1.19$$

$$\mathfrak{f}_i \text{ (from Fig. 14-1)} = 0.0066$$

$$n_p = 2$$

$$\phi_i = 1.02\left(\frac{\mu_i}{\mu_w}\right)^{0.14} = 1.02(2.25)^{0.14} = 1.14$$

$$-\Delta P_i = \frac{(1.19)(2)(0.0066)(752{,}000)^2(8.9)(2)}{(3600)^2(32.17)(49)(0.584/12)(1.14)} = 140 \text{ psf}$$

The pressure drop due to friction through the tube side of the exchanger is approximately 140 psf or 1 psi.

If the cost for power is \$0.02 per kilowatthour, the pumping cost due to frictional pressure drop on the tube side of the exchanger is $(140)(70{,}000)(0.02)/(49)(2.655 \times 10^6)$ = \$0.0015 per hour.

The low power cost and low pressure drop indicate that a higher liquid velocity would be beneficial, since it would give a better heat-transfer coefficient and have little effect on the total cost.

Example 4. Estimation of Film Coefficient and Pressure Drop on Shell Side in a Shell-and-Tube Exchanger. A shell-and-tube heat exchanger with one shell pass and one tube pass is being used as a cooler. The cooling medium is water on the shell side of the exchanger. Five segmental baffles with a 25 per cent cut are used on the shell side, and the baffles are spaced equally 2 ft apart. The safety factor F_s for use in evaluating the shell-side film coefficient is 1.6. The inside diameter of the shell is 23 in. The OD of the tubes is 0.75 in., and the tubes are staggered. Clearance between tubes is 0.25 in., and the flow of water across the tubes is normal to this clearance. There is a total of 384 tubes in the exchanger, and the shell can be considered to be full-packed. Water flows through the shell side at a rate of 90,000 lb/hr. The average temperature of the water is 90°F, and the average temperature of the tube walls on the water side is 100°F. Under these conditions, estimate the heat-transfer coefficient for the water and the pressure drop due to friction on the shell side of the exchanger.

Solution

Average water-film temperature = 95°F
From the Appendix,
μ for water at 95°F = 0.724 centipoise
k for water at 95°F = 0.361 Btu/(hr)(sq ft)(°F/ft)
c_p for water at 95°F = 1 Btu/(lb)(°F)
ρ for water at 90°F = 62.1 lb/cu ft
μ for water at 100°F = 0.684 centipoise
Calculation of Reynolds number = D_oG_s/μ_f
$D_o = 0.75/12$ ft
$\mu_f = (0.724)(2.42)$ lb/(hr)(ft)

Free area for evaluation of G_s occurs at center plane of shell where number of tube rows normal to flow direction = 23 (0.75 + 0.25) = 23. Free area is based on the smallest flow area at the center plane. In this case, the transverse openings give the smallest free area.

$$\text{Free area between baffles} = \frac{(23)(0.25)(2)}{12} = 0.96 \text{ sq ft}$$

$$G_s = \frac{90{,}000}{0.96} = 94{,}000 \text{ lb/(hr)(sq ft)}$$

$$\frac{D_oG_s}{\mu_f} = \frac{(0.75)(94{,}000)}{(12)(0.724)(2.42)} = 3360$$

$$\left(\frac{c_p\mu}{k}\right)_f = \frac{(1)(0.724)(2.42)}{0.361} = 4.85$$

Equation (29) may be used under these conditions.

$$h_o = \frac{k_f}{D_o}\frac{a_o}{F_s}\left(\frac{D_oG_s}{\mu_f}\right)^{0.6}\left(\frac{c_p\mu}{k}\right)_f^{1/3}$$

$$a_o = 0.33 \qquad F_s = 1.6$$

$$h_o = \frac{(0.361)(12)(0.33)(3360)^{0.6}(4.85)^{1/3}}{(0.75)(1.6)} = 260 \text{ Btu/(hr)(sq ft)(°F)}$$

Determination of pressure drop due to friction. Equations (31) to (33) apply for this case:

$$-\Delta P_o = \frac{B_o 2 \mathfrak{f}' N_r G_s^2}{g_c \rho_o}$$

$$\mathfrak{f}' = \left[0.23 + \frac{0.11}{(x_T - 1)^{1.08}}\right]\left(\frac{D_o G_s}{\mu_f}\right)^{-0.15}$$

$$\mathfrak{f}' = 0.23 + \frac{0.11}{(1.0/0.75 - 1)^{1.08}}(3360)^{-0.15} = 0.175$$

B_o = roughly the number of tube crosses = number of baffles + 1 = 6. N_r = number of tube rows across which shell fluid flows = 23 minus the tube rows that pass through the cut portions of the baffles. With 25 per cent cut baffles, the fluid will flow across approximately one-half of the tubes. In this case, N_r will be taken as 14. This gives some allowance for neglecting friction due to reversal of flow direction and friction due to flow parallel to the tubes:

$$-\Delta P_o = \frac{(6)(2)(0.175)(14)(94{,}000)^2}{(32.17)(3600)^2(62.1)} = 10 \text{ psf}$$

Pressure drop due to friction on the shell side of the exchanger is approximately 10 psf

CONSIDERATIONS IN SELECTION OF HEAT-TRANSFER EQUIPMENT

When the design engineer selects heat-transfer equipment, he must consider the basic process-design variables and also many other factors, such as temperature strains, thickness of tubes and shell, types of baffles, tube pitch, and standard tube lengths. Under ordinary conditions, the mechanical design of an exchanger should meet the requirements of the ASME or API-ASME Safety Codes. The Tubular Exchanger Manufacturers Association publishes standards on general design methods and fabrication materials for tubular heat exchangers.

Tube Size and Pitch. The standard length of tubes in a shell-and-tube heat exchanger is 8, 12, or 16 ft, and these standard-length tubes are available in a variety of different diameters and wall thicknesses. Exchangers with small-diameter tubes are less expensive per square foot of heat-transfer surface than those with large-diameter tubes, because a given surface can be fitted into a smaller shell diameter; however, the small-diameter tubes are more difficult to clean. A tube diameter of ¾ or 1 in. OD is the most common size, but outside diameters ranging from ⅝ to 1½ in. are found in many industrial installations.

Tube-wall thickness is usually specified by the Birmingham wire gauge, and variations from the nominal thickness may be ±10 per cent for "average-wall" tubes and +22 per cent for "minimum-wall" tubes. Pressure, temperature, corrosion, and allowances for expanding the individual tubes into the tube sheets must be taken into consideration when the thickness is determined.

Tube pitch is defined as the shortest center-to-center distance between adjacent tubes, while the shortest distance between two tubes is designated as the *clearance*. In most shell-and-tube exchangers, the pitch is in the range of 1.25 to 1.50 times the tube diameter. The clearance should not be less than one-fourth of the tube diameter, and $^3/_{16}$ in. is usually considered to be a minimum clearance.

Tubes are commonly laid out on a square pattern or on a triangular pattern, as shown in Fig. 15-6. Although a square pitch has the advantage of easier external cleaning, the triangular pitch is sometimes preferred because it permits the use of more tubes in a given shell diameter. Table 7 indicates the number of tubes that can be placed in an exchanger with conventional tube sizes and pitches.

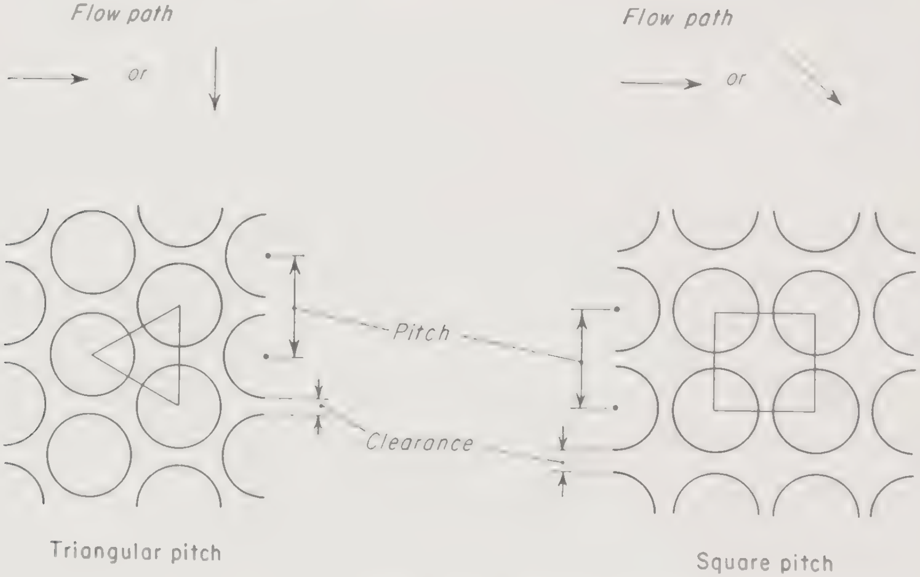

FIG. 15-6. Conventional tube-plate layouts.

Shell Size. For shell diameters up to 24 in., nominal pipe sizes apply to the shell. Inside diameters are usually indicated, and schedule number or wall thickness should also be designated. In general, a shell thickness of $^3/_8$ in. is used for shell diameters between 12 and 24 in., unless the fluids are extremely corrosive or the operating pressure on the shell side exceeds 300 psig.

Thermal Strains. Thermal expansion can occur when materials, such as the metal components of a heat exchanger, are heated. For example, in a shell-and-tube heat exchanger, thermal expansion can cause an elongation of both the tube bundle and the shell as the temperature of the unit is increased. Because the tube bundle and the shell may expand by dif-

TABLE 7. NUMBER OF TUBES IN CONVENTIONAL TUBE-SHEET LAYOUTS

Shell ID, in.	One-pass		Two-pass		Four-pass	
	Square pitch	Triangular pitch	Square pitch	Triangular pitch	Square pitch	Triangular pitch
			¾-in.-OD Tubes on 1-in. Pitch			
8	32	37	26	30	20	24
12	81	92	76	82	68	76
15¼	137	151	124	138	116	122
21¼	277	316	270	302	246	278
25	413	470	394	452	370	422
31	657	745	640	728	600	678
37	934	1074	914	1044	886	1012
			1-in.-OD Tubes on 1¼-in. Pitch			
8	21	21	16	16	14	16
12	48	55	45	52	40	48
15¼	81	91	76	86	68	80
21¼	177	199	166	188	158	170
25	260	294	252	282	238	256
31	406	472	398	454	380	430
37	596	674	574	664	562	632

ferent amounts, some arrangement may be necessary to reduce thermal strains. Figure 15-7 shows a fixed-tube-sheet exchanger with no allowance for expansion, while Figs. 15-8 and 15-9 illustrate two conventional types of exchangers with a floating head or a slip joint to relieve stresses caused by thermal expansion. Temperature stresses due to tube elongation can

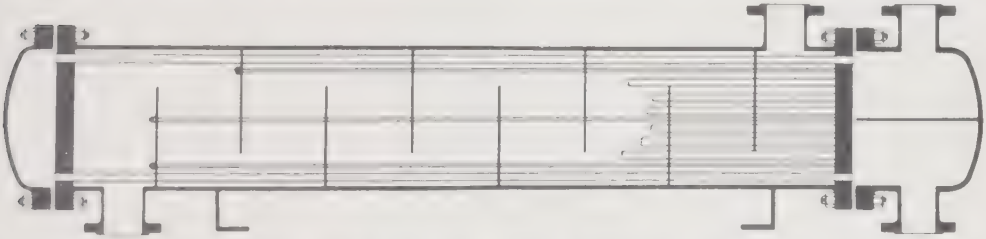

FIG. 15-7. Heat exchanger with fixed tube sheets, two tube passes, and one shell pass. (*Struthers-Wells Corporation.*)

also be avoided by using U-shaped tubes, and some exchangers have a U-type bellows loop or ring in the shell to handle thermal elongation of the shell.

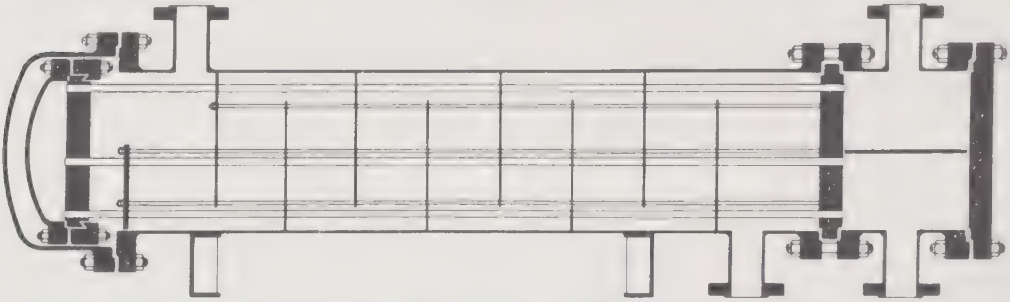

FIG. 15-8. Heat exchanger with internal floating head, two tube passes, and one shell pass. (*Struthers-Wells Corporation.*)

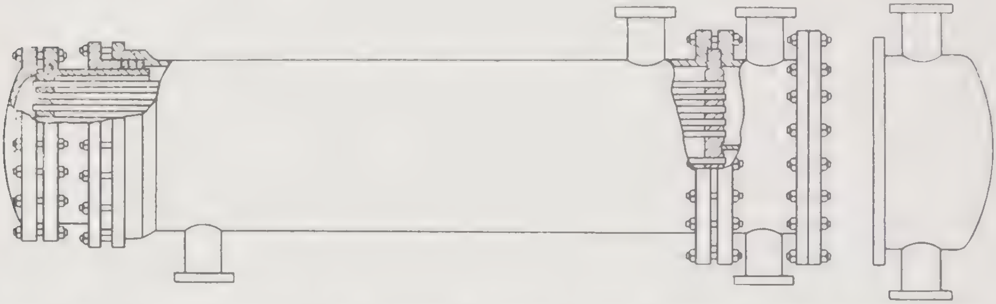

FIG. 15-9. Heat exchanger with external floating head, two tube passes, and one shell pass. (*Struthers-Wells Corporation.*)

Use of the fixed-head type of exchanger should be limited to exchangers with short tubes or to cases in which the maximum temperature difference between shell and tubes is less than 50°F. In general, floating-head exchangers with removable bundles are recommended for most services.*

Cleaning and Maintenance. Heat exchangers require periodic cleaning, tube replacements, or other maintenance work. The inside of straight tubes can be cleaned easily by forcing a wire brush or worm through the tubes, but cleaning of the outside of the tubes usually requires removal of the entire tube bundle from the exchanger. Consequently, many exchangers are provided with removable tube bundles, and the pitch and arrangement of the tubes is often dictated by the amount and type of cleaning that is required.

Baffles. Although the presence of baffles in the shell side of a shell-and-tube exchanger increases the pressure drop on the shell side, the advantage of better mixing of the fluid and increased turbulence more than offsets the pressure-drop disadvantage. The distance between baffles is known as the *baffle spacing*. In general, baffle spacing is not greater than a distance equal to the diameter of the shell or less than one-fifth of the shell diameter.

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* For method of estimating best number of floating heads, see E. N. Sieder, *Chem. & Met. Eng.*, **46**:322 (1939).

The most common type of baffle used in heat exchangers is the *segmental baffle*, illustrated in Fig. 15-10. Many segmental baffles have a baffle height that is 75 per cent of the inside diameter of the shell. This arrangement is designated as *25 per cent cut segmental baffles*. Other types of baffles include the *disk-and-doughnut baffle* and the *orifice baffle*, shown in Figs. 15-11 and 15-12. Longitudinal baffles of the permanent type (i.e., welded to the shell) or removable type are also found in some exchangers.

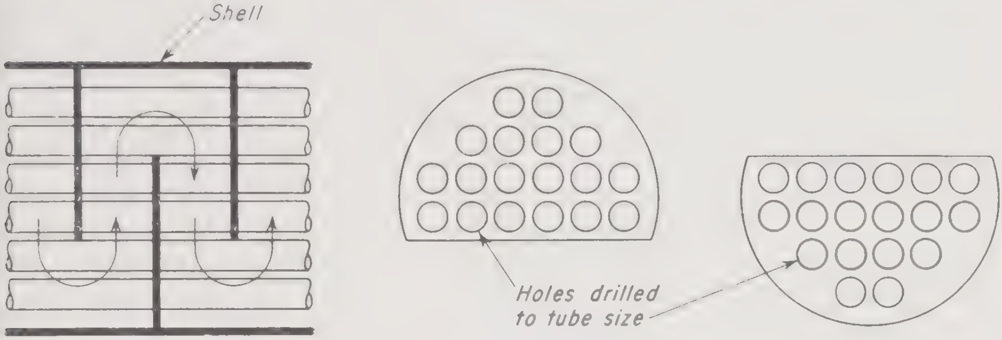

FIG. 15-10. Segmental baffles.

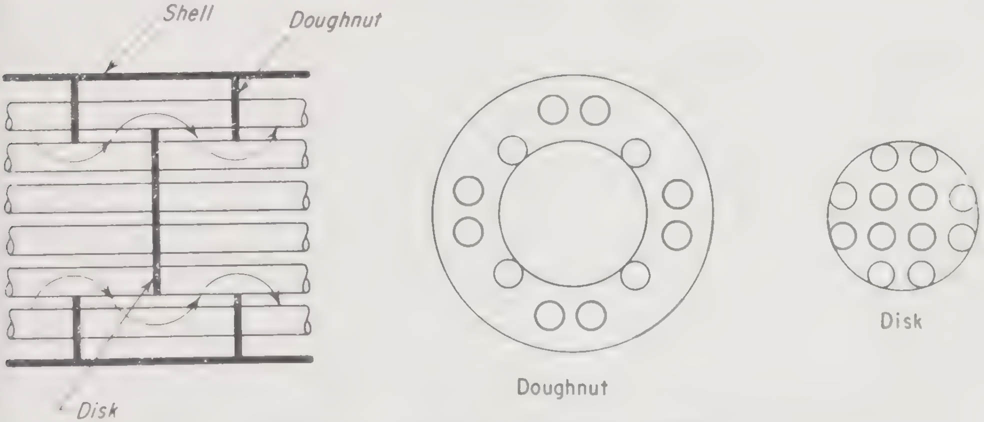

FIG. 15-11. Disk-and-doughnut baffles.

Segmental and disk-and-doughnut baffles contain tube-pass holes of size close to that of the diameter of the tubes. With these two types of baffles, the clearance between the tubes and the edge of the holes may range from 1 per cent to as high as 3 per cent of the tube diameter. As a result, some fluid passes through the clearance spaces, but the major portion of the fluid should flow between the baffles in a direction perpendicular to the tubes.

Orifice baffles should be spaced reasonably close together to produce frequent increases in fluid velocity through the orifice openings between the tubes and the baffles. This type of baffle should not be used for fluids with high fouling characteristics.

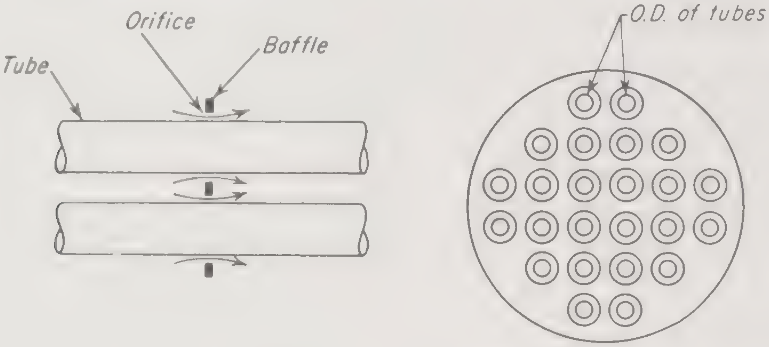

FIG. 15-12. Orifice baffle.

Straight tie rods are used to hold baffles in place. Usually, four to six rods of ⅛- to ½-in. diameter are necessary. These are fitted to the fixed tube sheet, and short lengths of pipe sleeves are placed around the tie rods to form shoulders between adjacent baffles. The thickness of baffle plates should be at least twice the thickness of the tube walls and is ordinarily in the range of ⅛ to ¼ in. The tube sheets should have a thickness at least as great as the outside diameter of the tubes. In industrial exchangers, ⅞ in. is ordinarily considered as a minimum thickness for tube sheets.

Fluid Velocities and Location of Fluids. The major factors involved in determining the best location for fluids in a heat exchanger are the fouling and corrosion characteristics of the fluids, pressure drop across the unit, materials costs, and general physical characteristics of the fluids and the exchanger. When one of the fluids is highly corrosive, it should flow inside the tubes to avoid the expense of corrosion-resistant materials of construction on the shell side. Because cleaning inside tubes is easier than external cleaning, consideration should always be given to locating the fluid with the greatest fouling tendencies inside the tubes. If the other factors are equal and one fluid is under high pressure, the expense of a high-pressure shell construction can be avoided by passing the high-pressure fluid through the tubes.

The velocities of the fluids passing through the shell side and the tube side of an exchanger can have a large influence on the heat-transfer coefficients and the pressure drop. At high velocities, the beneficial effects of large film coefficients can be counterbalanced by the detrimental effects of high pressure drop. If one of the fluids is much more viscous than the other, pressure drop on the tube side may be excessive when the viscous fluid is passed through the tubes at the velocity necessary for adequate rates of heat transfer. The effects of fluid velocities and viscosities, therefore, must be considered carefully before a final decision is made concerning the best routing of the fluids.

Ineffective Surface. In the course of heating a fluid, noncondensable gases, such as absorbed air, may be evolved. If these gases are not removed, they can collect in the exchanger and form an effective blanket around some of the heat-transfer surface. Adequate provision, therefore, should be made for venting noncondensables. The heat-transfer surface can also become ineffective because of build-up of condensate when condensing vapors are involved. Consequently, drains, steam traps with bypasses, and sight glasses to indicate condensate level are often necessary auxiliaries on heat exchangers. When high pressures are used, relief valves or rupture disks may be essential for protection. Vapor blanketing can occur in boilers if the critical temperature-difference driving force is exceeded, and the design engineer must take this factor into consideration. Inadequate baffling on the shell side of an exchanger can result in poor distribution of the shell-side fluid, with a resulting ineffective use of the available surface area.

Use of Water in Heat Exchangers. Because of the abundance of water and its high heat capacity, this material is used extensively as a heat-exchange medium. At high temperatures, water exerts considerable corrosive action on steel, particularly if the water contains dissolved oxygen. Nonferrous metals, therefore, are often employed in heat exchangers when water is one of the fluids. To reduce costs, the water may be passed through the more expensive tubes, and the shell side of the exchanger can be constructed of steel. When water is used in contact with steel, a large corrosion allowance should be included in the mechanical design.

Liquid mixtures that contain solids tend to foul heat exchangers very rapidly, because the solids can settle out and bake into a cake on the hot walls. This difficulty can be reduced by passing the fluid through the exchanger at a velocity which is sufficient to keep the solids in suspension. As a standard practice, a fluid velocity of at least 3 fps should be maintained in an exchanger when the fluid is water. This minimum velocity is particularly important if the water is known to contain any suspended solids. Since it is very difficult to eliminate low-velocity pockets on the shell side of an exchanger, water that contains suspended solids should be passed through the tube side of the exchanger.

As far as possible, suspended solids should be removed from water before it enters a heat exchanger. This can be accomplished by use of settling tanks or filters. Screen filters are commonly used on water lines to remove debris, such as sticks, pebbles, or pieces of algae, but a screen filter will not remove finely dispersed solids.

Another difficulty encountered when water is employed as a heat-transfer medium is the formation of mineral scale. At temperatures higher than 120°F, the formation of scale from water of average mineral and air content tends to become excessive. Consequently, an outlet water temperature above 120°F should be avoided. In many cases, it is advisable to soften the water by a chemical treatment before using it in a heat exchanger. Hot water leaving a heat exchanger may be reused by employing a cooling tower to lower the temperature of the water. This reduces both the softening costs and the amount of water that must be purchased.

Use of Steam in Heat Exchangers. Steam has a high latent heat of condensation per unit weight and is, therefore, very effective as a heating medium. Exhaust steam is often available as a by-product from power plants. Because exhaust steam usually has a saturation temperature in the range of 215 to 230°F, the material is useful for heating only in the delivery-temperature range below about 200°F. If a material must be heated to higher temperatures, process steam is necessary. At a pressure of 200 psig, the condensing temperature of steam is 382°F. Consequently, when delivery temperatures much higher than 300°F are required, the high steam pressure necessary may eliminate steam as a useful heating medium. Under these conditions, another heating medium, such as Dowtherm, which does not require high pressures, might be chosen.

The film coefficients of heat transfer for pure condensing steam are ordinarily in the range of 1000 to 3000 Btu/(hr)(sq ft)(°F). The condensing-steam film, therefore, is seldom the controlling resistance in a heat exchanger, and approximate values of steam-film coefficients are usually adequate for design purposes.* If the steam is superheated, it is standard design practice to neglect the superheat and assume all the heat is delivered at the condensing temperature corresponding to the steam pressure. Similarly, subcooling of the condensate and pressure drop due to friction on the steam side of the exchanger are usually neglected. Under these conditions of assumed isothermal condensation, the true temperature-difference driving force is the same as the logarithmic-mean value.

Specifications for Heat Exchangers. The design engineer should consider both process design and mechanical design when he prepares the specifications for a heat exchanger. The fabricator ordinarily has a plant that is tooled to produce standard parts at the least cost and in the shortest time. Consequently, the design engineer should not attempt to specify every detail on an exchanger unless he is thoroughly familiar with the fabricator's equipment and methods. On the other hand, the specifications must be sufficiently complete to permit an adequate evaluation by the fabricator.

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* For design estimates under ordinary conditions, a conservative value of 1500 Btu/(hr)(sq ft)(°F) is often assumed for the condensing-steam film coefficient.

The following list presents the basic information that should be supplied to a fabricator in order to obtain a price estimate or firm quotation on a proposed heat exchanger:

Process information

1. Fluids to be used
    a. Include fluid properties if they are not readily available to the fabricator
2. Flow rates or amounts of fluids
3. Entrance and exit temperatures
4. Amount of vaporization or condensation
5. Operating pressures and allowable pressure drops
6. Fouling factors
7. Rate of heat transfer

Mechanical information

1. Size of tubes
    a. Diameter
    b. Length
    c. Wall thickness
2. Tube layout and pitch
    a. Horizontal tubes
    b. Vertical tubes
3. Maximum and minimum temperatures and pressures
4. Necessary corrosion allowances
5. Special codes involved
6. Recommended materials of construction

Some of the preceding information can be presented in the form of suggestions, with an indication of the reasons for the particular choice. This would apply, in particular, to such items as fouling factors, tube layout, codes, and materials of construction. An example of a typical specification table for heat exchangers is presented in Fig. 13-1.

COSTS FOR HEAT-TRANSFER EQUIPMENT

The major factors that can influence the cost for heat-transfer equipment are indicated in the following list:

1. Heat-transfer area
2. Tube diameter and gauge
3. Tube length
4. Pressure
5. Materials of construction for tubes and shell
6. Degree and type of baffling
7. Supports, auxiliaries, and installation
8. Special features, such as floating heads; removable bundles; multipass, finned surfaces; and U bends

Certain manufacturers specialize in particular types of exchangers and can, therefore, give lower quotations on their specialties than other manufacturers. As a result, price quotations should be obtained from several

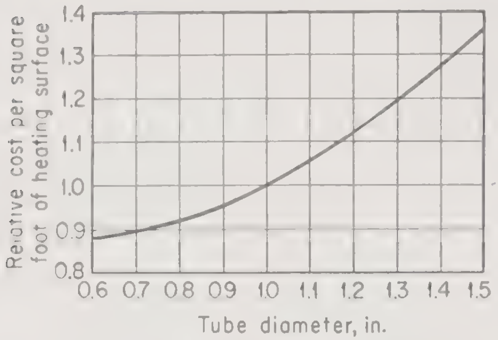

FIG. 15-13. Effect of tube diameter on cost of conventional shell-and-tube heat exchangers.

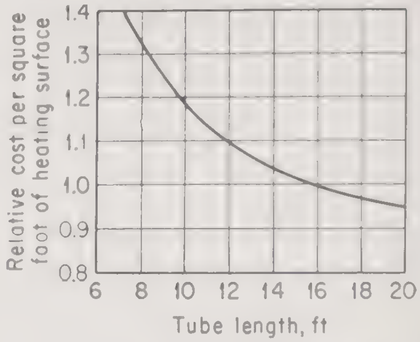

FIG. 15-14. Effect of tube length on cost of conventional shell-and-tube heat exchangers.

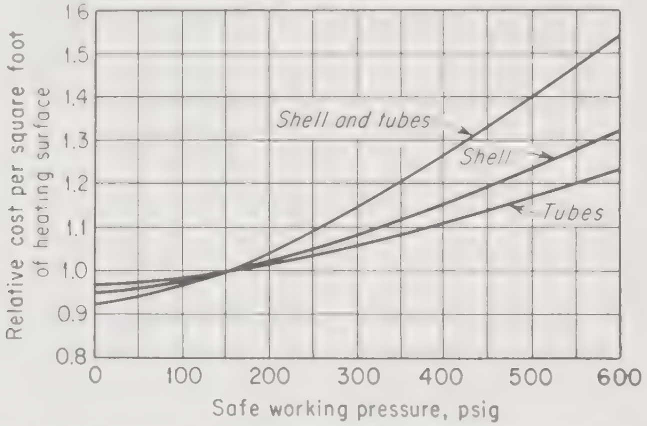

FIG. 15-15. Effect of operating pressure on cost of conventional shell-and-tube heat exchangers.

TABLE 8. RELATIVE COST FOR SHELL-AND-TUBE HEAT EXCHANGERS AS FUNCTION OF TUBE-SIDE MATERIAL OF CONSTRUCTION *†

Carbon-steel shell

Tube material	*Relative cost for exchanger*
Steel	1.0
Aluminum	1.2
Copper or brass	1.4
70-30 cupronickel	1.6
Stainless steel type 304	2.0
Monel	2.1
Stainless steel type 347	2.2
Nickel	2.3
Stainless steel type 316	2.3
Inconel	2.4

* J. H. Perry, "Chemical Engineers' Handbook," 3d ed., McGraw-Hill Book Company, Inc., New York, 1950.

† F. L. Rubin, *Chem. Eng.*, **64**(5):257 (1957).

manufacturers before a firm cost is listed. Figures 15-13 through 15-16 and Table 8 present average cost data for conventional heat-transfer equipment. Unless otherwise indicated, the data apply to shell-and-tube exchangers with one floating head, segmental baffles, 1-in.-OD tubes 16 ft long, and a safe working pressure of 150 psig. These data must be regarded as approximate and should be used only for preliminary rough estimates.

Relative Costs. The relative effect of tube diameter, tube length, and operating pressure on the purchased cost of heat exchangers is shown in Figs. 15-13 through 15-15.* If two floating heads are used in a single shell in place of one floating head, the exchanger cost will be increased by approximately 30 per cent, and a decrease in cost of about 10 to 15 per cent occurs if fixed tube sheets or U tubes are used instead of one floating head. Table 8 lists relative costs for tube-and-shell heat exchangers on the basis of the material of construction used for the tubes.

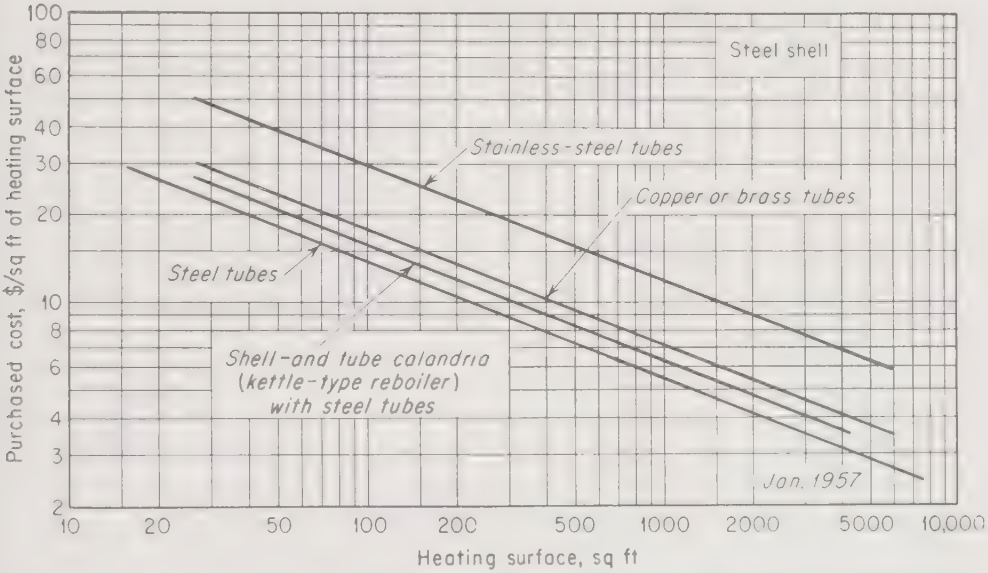

FIG. 15-16. Costs for conventional shell-and-tube heat exchangers. (Heating surface = A_o.)

Costs per Square Foot of Heating Surface.† Figure 15-16 shows approximate costs per square foot of heating surface for conventional floating-head exchangers with various materials of construction. Costs for forced-

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* E. N. Sieder, *Chem. & Met. Eng.*, **46**:322 (1939).

† R. S. Aries and R. D. Newton, "Chemical Engineering Cost Estimation," McGraw-Hill Book Company, Inc., New York, 1955.

H. Bliss, *Chem. Eng.*, **54**(5):126; **54**(6):100 (1947).

C. H. Chilton, *Chem. Eng.*, **56**(6):97 (1949).

F. L. Rubin, *Chem. Eng.*, **60**(5):201; **60**(7):177; **60**(9):229; **60**(10):196 (1953).

O. T. Zimmerman and I. Lavine, "Chemical Engineering Costs," Industrial Research Service, Dover, N.H., 1950.

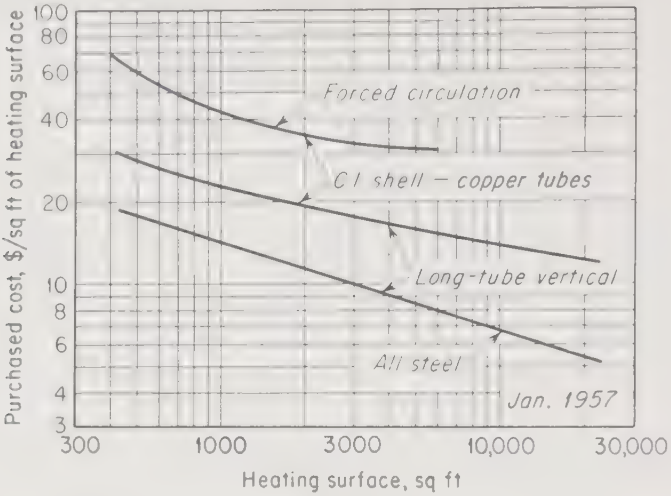

Fig. 15-17. Costs for long-tube vertical and forced-circulation evaporators complete with condensers and pumps.

circulation evaporators and long-tube evaporators are presented in Fig. 15-17.

OPTIMUM DESIGN OF HEAT EXCHANGERS

Two types of quantitative problems are commonly encountered by the design engineer when he is dealing with heat-transfer calculations. The first type is illustrated by Examples 3 and 4 in this chapter. In these examples, all of the design variables are set, and the calculations involve only a determination of the indicated nonvariant quantities. The conditions specified for Examples 3 and 4 give low pressure drops through the exchangers. Alternative conditions could be specified which would give higher pressure drops and less heat-transfer area. By choosing various conditions, the engineer could ultimately arrive at a final design that would give the least total cost for fixed charges and operation. Thus, the second type of quantitative problem involves conditions in which at least one variable is not fixed, and the goal is to obtain an optimum economic design.

In general, increased fluid velocities result in larger heat-transfer coefficients and, consequently, less heat-transfer area and exchanger cost for a given rate of heat transfer. On the other hand, the increased fluid velocities cause an increase in pressure drop and greater pumping costs. The optimum economic design occurs at the conditions where the total cost is a minimum. The basic problem, therefore, is to minimize the sum of the variable annual costs for the exchanger and its operation.

General Case *

The design of most heat exchangers involves initial conditions in which the following variables are known:

1. Process-fluid rate of flow
2. Change in temperature of process fluid
3. Inlet temperature of utility fluid (for cooling or heating)

With this information, the engineer must prepare a design for the optimum exchanger that will meet the required process conditions. Ordinarily, the following results must be determined:

1. Heat-transfer area
2. Exit temperature and flow rate of utility fluid
3. Number, length, diameter, and arrangement of tubes
4. Tube-side and shell-side pressure drops

The variable annual costs of importance are the fixed charges on the equipment, the cost for the utility fluid, and the power cost for pumping the fluids through the exchanger. The total annual cost for optimization, therefore, can be represented by the following equation:

$$C_T = A_o K_F C_{A_o} + w_u H_y C_u + A_o E_i H_y C_i + A_o E_o H_y C_o \tag{35}$$

where C_T = total annual variable cost for heat exchanger and its operation, \$/year

C_{A_o} = installed cost of heat exchanger per unit of outside-tube heat-transfer area, \$/sq ft

C_u = cost of utility fluid, \$/lb

C_i = cost for supplying 1 ft-lb force to pump fluid flowing through inside of tubes, \$/ft-lb force

C_o = cost for supplying 1 ft-lb force to pump fluid flowing through shell side of unit, \$/ft-lb force

A_o = area of heat transfer, sq ft; subscript *o* designates outside of tubes

K_F = annual fixed charges including maintenance, expressed as a fraction of initial cost for completely installed unit, dimensionless

w_u = flow rate of utility fluid, lb/hr

H_y = hours of operation per year, hr/year

E_i = power loss inside tubes per unit of outside tube area, ft-lb force/(hr)(sq ft)

E_o = power loss outside tubes per unit of outside tube area, ft-lb force/(hr)(sq ft)

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* The analysis presented in this section is similar to that of M. Cichelli and M. Brinn, *Chem. Eng.*, **63**(5):196 (1956). Optimum design methods for heat exchangers are also presented by W. H. McAdams, "Heat Transmission," 3d ed., McGraw-Hill Book Company, Inc., New York, 1954.

An optimum design could be developed from Eq. (35) by the laborious procedure of direct trial and error, taking all possible variables into consideration; however, the procedure can be simplified considerably by using the method of partial derivatives.

Under ordinary circumstances, the effect of tube diameter on total cost at the optimum operating conditions is not great, and a reasonable choice of tube diameter, wall thickness, and tube spacing can be specified at the start of the design. Similarly, the number of tube passes is usually specified. If a change in phase of one of the fluids occurs (for example, if the utility fluid is condensing steam), solution of Eq. (35) for optimum conditions can often be simplified. For the case of no change in phase, the solution can become complex, because the velocities and resulting power costs and heat-transfer coefficients can be varied independently over a wide range of values. In the following analysis, the general case of steady-state heat transfer in shell-and-tube exchangers with no change in fluid phase is considered, and a specified tube diameter, wall thickness, number of passes, and arrangement of baffles and tubes are assumed. Simplifications are indicated for the common conditions of turbulent flow.

Choice of Primary Independent Variables. The heat-transfer area A_o can be related to the flow rates and the temperature changes by an over-all heat balance and the rate equation. If heat losses are assumed as negligible and q is designated as the rate of heat transfer to the utility fluid,

$$q = w_u c_{p_u}(t_2 - t_1) = w' c'_p(t'_1 - t'_2) = U_o A_o \, \Delta t_m \qquad (36)\,^*$$

where the primes refer to the process fluid. Subscript 1 refers to the entering temperature, and subscript 2 refers to the leaving temperature.

From Eq. (36),

$$w_u = \frac{q}{c_{p_u}(\Delta t_1 - \Delta t_2 + t'_1 - t'_2)} \qquad (37)$$

where $\Delta t_1 = t'_2 - t_1$ and $\Delta t_2 = t'_1 - t_2$. Since q, c_{p_u}, Δt_1, t'_1, and t'_2 are constant, w_u is a function only of the independent variable Δt_2.†

The area A_o is known if U_o and Δt_m are fixed. The over-all coefficient U_o is known if the inside and outside film coefficients, h_i and h_o, are fixed, and, for a given number of tube passes, Δt_m varies only with changes in

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[*] Under these conditions, q is negative if the exchanger is used for heating the process fluid, and q is positive if the process fluid is cooled.

[†] The heat capacity, viscosity, and density of the fluids are taken as constant at an assumed average temperature. This assumption is adequate for most cases. If greater precision is necessary, the results of the initial calculation can be used to obtain new values for the physical constants, and the corresponding optimum conditions can be determined.

Δt_2. Therefore, A_o is a function of h_i, h_o, and Δt_2, as shown by the following equations:

$$\frac{\Delta t_m}{q} = \frac{1}{U_o A_o} = \frac{1}{A_o}\left(\frac{D_o}{D_i h_i} + \frac{1}{h_o} + R_{dw}\right) \tag{38}$$

$$\frac{F_T(\Delta t_2 - \Delta t_1)}{q \ln (\Delta t_2/\Delta t_1)} = \frac{1}{U_o A_o} = \frac{1}{A_o}\left(\frac{D_o}{D_i h_i} + \frac{1}{h_o} + R_{dw}\right) \tag{39}$$

where U_o = over-all coefficient of heat transfer based on outside tube area A_o

F_T = correction factor on logarithmic-mean temperature difference for counterflow to account for number of passes; $F_T = 1$ if unit is counterflow and single-pass on shell and tube sides (see Fig. 15-2)

R_{dw} = combined resistance of tube wall and scaling or dirt factors,

$$\frac{D_o x_w}{k_w D_{w_{\text{log mean}}}} + \frac{D_o}{D_i h_{d_i}} + \frac{1}{h_{d_o}}$$

For a set diameter and tube arrangement, Eqs. (26) and (29) show that h_i is fixed by the mass velocity G inside the tubes and h_o is fixed by the mass velocity G_s outside the tubes. Similarly, since the heat-transfer area A_o, mass velocities, and flow rates determine the length of the tubes L, Eqs. (30) and (31) show that E_i and E_o are functions of A_o, flow rates, and, respectively, G and G_s.* Thus, E_i and E_o are functions of h_i, h_o, and Δt_2.

The variables in Eq. (35) are A_o, w_u, E_i, and E_o, and their values are set if h_i, h_o, and Δt_2 are known. Partial differentiation, therefore, of Eq. (35) with respect to the three independent variables h_i, h_o, and Δt_2 would lead to a solution for the optimum conditions. However, the resulting equations are cumbersome, and the procedure is simplified by retaining the following four variables:

1. Tube-inside coefficient of heat transfer, h_i
2. Tube-outside coefficient of heat transfer, h_o
3. Temperature-difference driving force for counterflow based on temperature of utility fluid at exit from exchanger, $\Delta t_2 = t_1' - t_2$
4. Outside tube area of heat transfer, A_o

Optimization Procedure. The first step in the optimization procedure is to express Eq. (35) in terms of the fundamental variables. The following relationships for power loss inside tubes and power loss outside tubes are developed in Table 9 for conditions of turbulent flow and shell-side fluid flowing in a direction normal to the tubes:

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* See Eqs. (*B*) and (*H*) in Table 9.

$$E_i = \psi_i h_i^{3.5} \tag{40}$$

$$E_o = \psi_o h_o^{4.75} \tag{41}$$

where

$$\psi_i = B_i \left[\frac{12{,}200 D_i^{1.5} \mu_i^{1.83} (\mu_{wt}/\mu_i)^{0.63}}{g_c D_o \rho_i^2 k_i^{2.33} c_{pt}^{1.17}} \right] \tag{40a}$$

$$\psi_o = \frac{B_o}{n_b} \frac{N_r N_c}{N_t} \left[\frac{2b_o D_c D_o^{0.75} F_s^{4.75} \mu_{f_o}^{1.42}}{\pi a_o^{4.75} g_c \rho_o^2 k_{f_o}^{3.17} c_{p_{fo}}^{1.58}} \right] \tag{41a}$$

All the terms in the brackets are set by the design conditions or can be approximated with good accuracy on the first trial. The values of B_i and

TABLE 9. DEVELOPMENT OF EQUATIONS FOR OPTIMIZATION OF HEAT-EXCHANGER DESIGN

Conditions: Turbulent flow in shell-and-tube heat exchangers with cross flow on the shell side.

Power Loss inside Tubes

(A) $\Delta p_i = \dfrac{B_i 2\mathfrak{f}_i G^2 L n_p}{g_c \rho_i D_i \phi_i} = \dfrac{2\mathfrak{f}_i G_i^2 L n_p}{g_c \rho_i D_i \phi_i} + (F_e + F_c + F_r) n_p \rho_i$ (Eq. 30)

(A1) $\phi_i = 1.02 \left(\dfrac{\mu_i}{\mu_{w_i}} \right)^{0.14}$

(A2) $S_i = \dfrac{\pi D_i^2 N_t}{4 n_p}$

(A3) $A_o = N_t \pi D_o L$

where S_i = cross-sectional flow area inside tubes per pass
N_t = total number of tubes in exchanger = (number of tubes per pass) n_p

(B) $E_i = \dfrac{\Delta p_i w_i}{\rho_i A_o} = \dfrac{\Delta p_i G S_i}{\rho_i A_o} = \dfrac{\Delta p_i G D_i^2}{4 \rho_i D_o L n_p}$

For turbulent flow in tubes,

(C) $\mathfrak{f}_i = \dfrac{0.046}{(N_{\text{Re}})^{0.2}} = \dfrac{0.046}{(D_i G/\mu_i)^{0.2}}$ (Chap. 14, Eq. 7*a*)

Combining Eqs. (*A*), (*B*), and (*C*),

(D) $E_i = \dfrac{0.023 B_i \mu_i^{0.2} D_i^{0.8} G^{2.8}}{g_c D_o \rho_i^2 \phi_i}$

(E) $\dfrac{h_i D_i}{k_i} = 0.023 \left(\dfrac{D_i G}{\mu_i} \right)^{0.8} \left(\dfrac{c_{p_i} \mu_i}{k_i} \right)^{1/3} \left(\dfrac{\mu_i}{\mu_{wt}} \right)^{0.14}$ (Eq. 26)

(E1) $G = \left[\dfrac{h_i D_i^{0.2} \mu_i^{0.8}}{0.023 k_i} \left(\dfrac{k_i}{c_{p_i} \mu_i} \right)^{1/3} \left(\dfrac{\mu_{w_i}}{\mu_i} \right)^{0.14} \right]^{1.25}$

TABLE 9. DEVELOPMENT OF EQUATIONS FOR OPTIMIZATION OF HEAT-EXCHANGER DESIGN (*Continued*)

Combining Eqs. (*A*1), (*D*), and (*E*1),

$$(F) \quad E_i = h_i^{3.5} B_i \frac{D_i^{1.5} \mu_i^{1.83} (\mu_{w_i}/\mu_i)^{0.63}}{(1.02)(0.023)^{2.5} g_c D_o \rho_i^2 k_i^{2.33} c_{p_i}^{1.17}}$$

$$\frac{1}{(1.02)(0.023)^{2.5}} = 12{,}200$$

Power Loss outside Tubes

$$(G) \quad \Delta p_o = \frac{B_o 2 f' N_r G_s^2}{g_c \rho_o} \qquad \text{(Eq. 31)}$$

$$(H) \quad E_o = \frac{\Delta p_o w_o}{\rho_o A_o} = \frac{\Delta p_o G_s S_o}{\rho_o A_o} = \frac{\Delta p_o G_s S_o}{\rho_o N_t \pi D_o L}$$

$$(I) \quad S_o = \frac{N_c D_c L}{n_b}$$

where S_o = shell-side free-flow area across shell axis
N_c = number of clearances between tubes for flow of shell-side fluid across shell axis
D_c = clearance between tubes to give smallest free area across shell axis
n_b = number of baffle spaces = number of baffles + 1

For turbulent flow across tubes,

$$(J) \quad f' = b_o \left(\frac{D_o G_s}{\mu_{f_o}}\right)^{-0.15} \qquad \text{(Eq. 32)}$$

See Eqs. (33) and (34) for values of b_o in terms of tube size and arrangement. Combining Eqs. (*G*), (*H*), (*I*), and (*J*),

$$(K) \quad E_o = \frac{2 B_o b_o \mu_{f_o}^{0.15} D_c G_s^{2.85} N_r N_c}{\pi g_c D_o^{1.15} \rho_o^2 n_b N_t}$$

$$(L) \quad \frac{h_o D_o}{k_{f_o}} = \frac{a_o}{F_s} \left(\frac{D_o G_s}{\mu_{f_o}}\right)^{0.6} \left(\frac{c_{p_o} \mu_o}{k_o}\right)_f^{\frac{1}{3}} \qquad \text{(Eq. 29)}$$

a_o = 0.33 for staggered tubes and 0.26 for in-line tubes

$$(L1) \quad G_s = \left[\frac{h_o D_o^{0.4} \mu_{f_o}^{0.6} F_s}{k_{f_o} a_o} \left(\frac{k_o}{c_{p_o} \mu_o}\right)_f^{\frac{1}{3}}\right]^{1.67}$$

Combining Eqs. (*K*) and (*L*1),

$$(M) \quad E_o = h_o^{4.75} \frac{B_o}{n_b} \frac{N_r N_c}{N_t} \frac{2 b_o D_c D_o^{0.75} F_s^{4.75} \mu_{f_o}^{1.42}}{\pi a_o^{4.75} g_c \rho_o^2 k_{f_o}^{3.17} c_{p_{f_o}}^{1.58}}$$

B_o/n_b are not completely independent of the film coefficients, but they do not vary enough to be critical. As a first approximation, B_i is usually close to 1, and B_o is often taken to be equal to or slightly greater than the number of baffle passes n_b. The value of the safety factor F_s depends on the amount of bypassing, and it is often taken as 1.6 for design estimates. The ratio N_rN_c/N_t depends on the tube layout and baffle arrangement. For rectangular tube bundles and no baffles, this ratio is equal to 1.0. For other tube layouts and segmental baffles, the ratio is usually in the range of 0.6 to 1.2.

Equation (35) can now be expressed in terms of the primary variables Δt_2, h_i, h_o, and A_o:

$$C_T = A_oK_FC_{A_o} + \frac{qH_yC_u}{c_{pu}(\Delta t_1 - \Delta t_2 + t_1' - t_2')} + A_o\psi_i h_i^{3.5}H_yC_i + A_o\psi_o h_o^{4.75}H_yC_o \tag{42}$$

Only three of the four variables in Eq. (42) are independent. Under these conditions, optimization can be accomplished by use of the Lagrange multiplier method.* The necessary relationship for applying the constant Lagrangian multiplier λ is given by Eq. (43):

$$\lambda\left[\frac{F_T(\Delta t_2 - \Delta t_1)}{q\ln(\Delta t_2/\Delta t_1)} - \frac{1}{A_o}\left(\frac{D_o}{D_ih_i} + \frac{1}{h_o} + R_{dw}\right)\right] = 0 \tag{43}$$

Equations (42) and (43) can now be added to give the following equation for optimization by partial differentiation with respect to each of the four primary variables:

$$C_T = A_oK_FC_{A_o} + \frac{qH_yC_u}{c_{pu}(\Delta t_1 - \Delta t_2 + t_1' - t_2')} + A_o\psi_i h_i^{3.5}H_yC_i + A_o\psi_o h_o^{4.75}H_yC_o + \lambda\left[\frac{F_T(\Delta t_2 - \Delta t_1)}{q\ln(\Delta t_2/\Delta t_1)} - \frac{1}{A_o}\left(\frac{D_o}{D_ih_i} + \frac{1}{h_o} + R_{dw}\right)\right] \tag{44}$$

Optimum Value of h_o. The following relationship between the optimum values of h_i and h_o is obtained by taking the partial derivative of Eq. (44) with respect to h_i and then with respect to h_o, setting the results equal to zero, and eliminating A_o and λ:

$$\frac{\partial C_T}{\partial h_i} = 3.5A_{o,opt}\psi_i h_{i,opt}^{2.5}H_yC_i + \frac{\lambda D_o}{A_{o,opt}D_ih_{i,opt}^2} = 0 \tag{45a}$$

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* I. S. Sokolnikoff and E. S. Sokolnikoff, "Higher Mathematics for Engineers and Physicists," McGraw-Hill Book Company, Inc., New York, 1941.

$$\frac{\partial C_T}{\partial h_o} = 4.75 A_{o,opt} \psi_o h_{o,opt}^{3.75} H_y C_o + \frac{\lambda}{A_{o,opt} h_{o,opt}^2} = 0 \tag{45b}$$

$$h_{o,opt} = \left(\frac{0.74 \psi_i C_i D_i}{\psi_o C_o D_o} \right)^{0.17} h_{i,opt}^{0.78} \tag{45c}$$

Optimum Value of h_i. The optimum value of h_i can be determined by setting the partial derivatives of Eq. (44) with respect to A_o and with respect to h_i equal to zero and eliminating A_o and λ. This gives a result with $h_{i,opt}$ and $h_{o,opt}$ as the only unknowns, and simultaneous solution with Eq. (45*c*) yields Eq. (46*b*), where $h_{i,opt}$ is the only unknown.

$$\frac{\partial C_T}{\partial A_o} = K_F C_{A_o} + \psi_i h_{i,opt}^{3.5} H_y C_i + \psi_o h_{o,opt}^{4.75} H_y C_o + \frac{\lambda}{A_{o,opt}^2} \left(\frac{D_o}{D_i h_{i,opt}} + \frac{1}{h_{o,opt}} + R_{dw} \right) = 0 \tag{46a}$$

$$h_{i,opt}^{3.5} \left[2.5 \psi_i H_y C_i + \frac{3.5 \psi_i H_y C_i D_i R_{dw} h_{i,opt}}{D_o} + 2.9 \left(\frac{\psi_i C_i D_i}{D_o} \right)^{0.83} (\psi_o C_o)^{0.17} H_y h_{i,opt}^{0.22} \right] = K_F C_{A_o} \tag{46b}$$

Optimum Value of U_o. A trial-and-error or graphical method can be used to obtain $h_{i,opt}$ from Eq. (46*b*). Then, by Eqs. (38) and (45*c*), the value of $U_{o,opt}$ can be determined as

$$U_{o,opt} = \left(\frac{D_o}{D_i h_{i,opt}} + \frac{1}{h_{o,opt}} + R_{dw} \right)^{-1} \tag{47}$$

Optimum Value of Δt_2. The value of $U_{o,opt}$ is now known, and $\Delta t_{2,opt}$ can be determined by setting the partial derivatives of Eq. (44) with respect to Δt_2 and with respect to A_o equal to zero and eliminating λ. The result can be combined with Eqs. (39) to (41) to give

$$\frac{F_T U_{o,opt} H_y C_u}{c_{pu}(K_F C_{A_o} + E_{i,opt} H_y C_i + E_{o,opt} H_y C_o)} = \left(1 + \frac{t_1' - t_2'}{\Delta t_1 - \Delta t_{2,opt}} \right) \left(\ln \frac{\Delta t_{2,opt}}{\Delta t_1} - 1 + \frac{\Delta t_1}{\Delta t_{2,opt}} \right) \tag{48}$$

Equation (48) can be solved for $\Delta t_{2,opt}$ by trial and error or by Fig. 15-18, which is a plot of Eq. (48).*

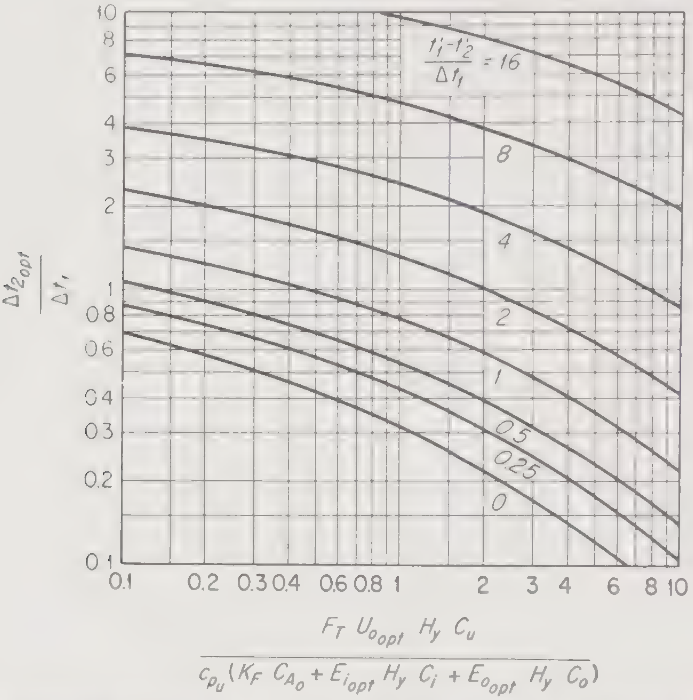

FIG. 15-18. Graphical solution of Eq. (48) for evaluation of optimum Δt_2 in heat exchangers.

Optimum Value of A_o. Since $\Delta t_{2,opt}$ and, therefore, $\Delta t_{m,opt}$ are now known, $A_{o,opt}$ can be determined directly from Eq. (38).

Optimum Value of G and G_s. Equations ($E1$) and ($L1$) in Table 9 give G_{opt} and $G_{s,opt}$, respectively, in terms of $h_{i,opt}$ and $h_{o,opt}$.

Optimum Value of w_u. The flow rate of the utility fluid (w_u) is set by the value of Δt_2. Therefore, when $\Delta t_{2,opt}$ is known, $w_{u,opt}$ can be calculated from Eq. (37).

Optimum Values of S_i and N_t. The optimum flow area inside the tubes per pass can be calculated from the following equation:

$$S_{i,opt} = \frac{w_i}{G_{opt}} \tag{49}$$

The optimum total number of tubes in the exchanger is

$$N_{t,opt} = \frac{4n_p S_{i,opt}}{\pi D_i^2} \tag{50}$$

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* A. P. Colburn, *Eng. Bull. Purdue Univ.*, vol. 26, ser. 84, no. 1, January, 1942.

Optimum Value of L. The optimum length per tube is set by the optimum heat-transfer area and the total number of tubes. Thus, for a given tube diameter

$$L_{opt} = \frac{A_{o,opt}}{\pi D_o N_{t,opt}} \tag{51}$$

Optimum Values of S_o, N_c, and n_b. The following equation gives the optimum shell-side free-flow area across the shell axis:

$$S_{o,opt} = \frac{w_o}{G_{s,opt}} \tag{52}$$

The number of clearances N_c for flow between tubes across the shell axis is determined by the number of tubes in the shell, the pitch of the tubes, and the arrangement of the tubes. For the common case of a cylindrical shell and transverse clearances giving the minimum free area, the following equations can be used to obtain an approximation of $N_{c,opt}$:[*][†]

With square pitch and N_t greater than 25

$$N_{c,opt} = 1.37(N_{t,opt})^{0.475} \tag{53}$$

With equilateral triangular pitch and N_t greater than 20

$$N_{c,opt} = 0.94 + \left(\frac{N_{t,opt} - 3.7)}{0.907}\right)^{1/2} \tag{54}$$

The optimum number of baffle spaces can be estimated by Eq. (I) in Table 9 as follows:

$$n_{b,opt} = \frac{N_{c,opt} D_c L_{opt}}{S_{o,opt}} \tag{55}$$

Summary of Procedure for General Case of Optimum Design

In the preceding analysis, consideration has been given to the general case in heat-exchanger design in which the following conditions apply:

1. The flow rate and necessary temperature change of the process fluid are known.
2. The inlet temperature of the utility fluid is known.
3. The exchanger is a shell-and-tube type with crossflow baffling, and flow is in the turbulent range on both the tube side and the shell side.
4. No partial phase changes occur.
5. Necessary safety factors are known.

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[*] W. H. McAdams, "Heat Transmission," 3d ed., p. 434, McGraw-Hill Book Company, Inc., New York, 1954.

[†] Equations (53) and (54) are based on the assumption that shell inside diameter/tube pitch = number of tubes in a row across the shell axis = number of clearances across the shell axis. No allowance is made for decrease in available tube space when more than one tube pass is used. The equations are general and are not necessarily limited to optimum conditions.

The following information may be specified for the design or can be assumed as a reasonable approximation:

1. Tube diameter, wall thickness, pitch, and arrangement
2. Number of tube passes
3. Heat-transfer resistance caused by tube walls, dirt, and scale

The following information must be assumed for the first trial and then checked when the optimum conditions are obtained (usually, no more than two trials are necessary, and an experienced engineer can often make adequate assumptions on the first trial):

1. Average bulk and film temperatures
2. Values for B_i (usually 1.0), B_o, n_b (usually 1.0), and N_r, N_c, N_t (usually 1.0)

The calculation procedure is as follows:

1. Determine $h_{i,opt}$ from Eq. (46*b*)
2. Determine $h_{o,opt}$ from Eq. (45*c*)
3. Determine $U_{o,opt}$ from Eq. (47)
4. Determine $\Delta t_{2,opt}$ from Eq. (48) or Fig. 15-18
5. Determine $A_{o,opt}$ from Eq. (39)
6. Determine G_{opt} and $G_{s,opt}$ from Eqs. (*E*1) and (*L*1) in Table 9
7. Determine $w_{u,opt}$ from Eq. (37)
8. Determine $S_{i,opt}$ and $N_{t,opt}$ from Eqs. (49) and (50)
9. Determine L_{opt} from Eq. (51)
10. Determine $S_{o,opt}$, $N_{c,opt}$, and $n_{b,opt}$ from Eqs. (52) through (55)
11. Check assumptions; if any are invalid, make new reasonable assumptions and repeat procedure

Example 5. Development of the Optimum Design for a Shell-and-Tube Heat Exchanger. A gas under pressure with properties equivalent to air must be cooled from 150 to 100°F. Cooling water is available at a temperature of 70°F. Use of a shell-and-tube heat exchanger with cooling water as the utility fluid has been proposed. On the basis of the following data and specifications, determine the tube length, number of tubes, and installed cost for the optimum exchanger which will handle 20,000 lb of the gas per hour.

1. Exchanger specifications
   - *a*. Steel shell-and-tube exchanger with cross-flow baffling.
   - *b*. Cooling water passes through shell side of unit.
   - *c*. One tube pass and countercurrent flow.
   - *d*. Tube OD = 1.0 in. Tube ID = 0.782 in.
   - *e*. 1¼-in. triangular pitch. Tubes are staggered.
2. Costs
   - *a*. Data presented in Fig. 15-16 are applicable.
   - *b*. Installation cost equals 15 per cent of purchased cost.
   - *c*. Annual fixed charges including maintenance equals 20 per cent of installed cost
   - *d*. Cost for cooling water (not including pumping cost) is \$0.005 per 1000 lb.
   - *e*. Cost for energy supplied to force the cooling water and the gas through the exchanger (including effect of pump-and-motor efficiency and cost) is \$0.02 per kwhr

3. General
   - *a.* Average absolute pressure of gas in exchanger is 10 atm.
   - *b.* Unit operates 7000 hr/year.
   - *c.* In the friction relations, B_i can be taken as 1.2, and B_o can be taken as equal to the number of tube crosses, assuming the optimum number of baffles can be installed in the unit.
   - *d.* The safety factor F_s for the outside film coefficient is 1.3.
   - *e.* Fouling coefficient for cooling water is 1500 Btu/(hr)(sq ft)(°F). Fouling coefficient for gas is 2000 Btu/(hr)(sq ft)(°F).
   - *f.* At the optimum conditions, flow on tube side and shell side is turbulent.
   - *g.* The factor $N_r N_c / N_t$ can be taken as 1.0.

Solution

Assumptions:
Exit temperature of cooling water = t_2 = 110°F
Average Δt over cooling-water film = 10 per cent of total Δt
Average Δt over air film = 80 per cent of total Δt
Purchased cost per square foot of outside heat-transfer area = \$12
Temperatures and physical properties:
$t_1' = 150°\text{F}$, $t_2' = 100°\text{F}$, $t_1 = 70°\text{F}$, $t_2 = 110°\text{F}$
$\Delta t_1 = t_2' - t_1 = 30°\text{F}$
Average bulk water temperature = 90°F
Average bulk gas temperature = 125°F
Average water-film temperature = 90 + (0.1/2)(35) = 91.8°F
Inside wall temperature = 125 − (0.8)(35) = 97°F
From Appendix: For water at 91.8°F, $k = 0.359$ Btu/(hr)(sq ft)(°F/ft), $\mu = (0.748)(2.42) = 1.81$ lb/(hr)(ft), $c_p = 1$ Btu/(lb)(°F). For water at 90°F, $\rho = 62.1$ lb/cu ft. For air at 125°F, $k = 0.0162$ Btu/(hr)(sq ft)(°F/ft), $\mu = (0.019)(2.42) = 0.046$ lb/(hr)(ft), $c_p = 0.25$ Btu/(lb)(°F), $\rho = (29)(492)(10)/(359)(460 + 125) = 0.68$ lb/cu ft. For air at 97°F, $\mu = (0.0185)(2.42) = 0.045$ lb/(hr)(ft).
Determination of optimum U_o. From Eq. (40*a*),

$$\psi_i = B_i \frac{12{,}200 D_i^{1.5} \mu_i^{1.83} (\mu_{w_i}/\mu_i)^{0.63}}{g_c D_o \rho_i^2 k_i^{2.33} c_{p_i}^{1.17}}$$

$$\psi_i = \frac{(1.2)(12{,}200)(0.782/12)^{1.5}(0.046)^{1.83}(0.045/0.046)^{0.63}}{(32.17)(3600)^2(\frac{1}{12})(0.68)^2(0.0162)^{2.33}(0.25)^{1.17}}$$

$$\psi_i = 4.1 \times 10^{-3}$$

From Eqs. (33) and (41*a*),

$$b_o = 0.23 + \frac{0.11}{(1.25-1)^{1.08}} = 0.72$$

$$\psi_o = \frac{B_o}{n_b} \frac{N_r N_c}{N_t} \frac{2 b_o D_c D_o^{0.75} F_s^{4.75} \mu_{f_o}^{1.42}}{\pi a_o^{4.75} g_c \rho_o^2 k_{f_o}^{3.17} c_{p_{f_o}}^{1.58}}$$

$$\psi_o = \frac{(1)(1)(2)(0.72)(0.25/12)(\frac{1}{12})^{0.75}(1.3)^{4.75}(1.81)^{1.42}}{(3.14)(0.33)^{4.75}(32.17)(3600)^2(62.1)^2(0.359)^{3.17}(1)^{1.58}}$$

$$\psi_o = 3.8 \times 10^{-11}$$

$$R_{dw} = \frac{x_w D_o}{k_w D_{w_{\text{log mean}}}} + \frac{D_o}{D_i h_{d_i}} + \frac{1}{h_{d_o}} = \frac{(0.109/12)(1/12)}{(26)(0.891/12)} + \frac{1/12}{(0.782/12)(2000)} + \frac{1}{1500}$$

$$= 1.7 \times 10^{-3}$$

$$C_i = C_o = \frac{\$0.02}{2.655 \times 10^6} \text{ per ft-lb force}$$

From Eq. (46*b*),

$$(h_{i,opt})^{3.5}(7000)\left(\frac{0.02}{2.655 \times 10^6}\right)\left[(2.5)(4.1 \times 10^{-3}) + \frac{(3.5)(4.1 \times 10^{-3})(0.782/12)(1.7 \times 10^{-3})h_{i,opt}}{1/12}\right.$$
$$\left. + 2.9\left(\frac{4.1 \times 10^{-3} \times 0.782}{1}\right)^{0.83}(3.8 \times 10^{-11})^{0.17}(h_{i,opt})^{0.22}\right] = (0.2)(12)(1.15)$$

By trial and error,

$$h_{i,opt} = 80 \text{ Btu/(hr)(sq ft)(°F)}$$

From Eq. (45*c*),

$$h_{o,opt} = \left[\frac{(0.74)(4.1 \times 10^{-3})(0.782/12)}{(3.8 \times 10^{-11})(1/12)}\right]^{0.17}(80)^{0.78} = 640 \text{ Btu/(hr)(sq ft)(°F)}$$

From Eq. (47),

$$U_{o,opt} = \left[\frac{1}{(0.782)(80)} + \frac{1}{640} + 0.0017\right]^{-1}$$

$$= (0.0160 + 0.00156 + 0.0017)^{-1} = (0.0193)^{-1}$$

$$= 52 \text{ Btu/(hr)(sq ft)(°F)}$$

$$\text{Per cent total } \Delta t \text{ over air film} = \frac{0.0160}{0.0193}(100) = 83 \text{ per cent}$$

$$\text{Per cent total } \Delta t \text{ over water film} = \frac{0.00156}{0.0193}(100) = 8.1 \text{ per cent}$$

Therefore, the per cent Δt assumptions are adequate.
Determination of optimum Δt_2:
$C_u = \$5 \times 10^{-6}$ per lb of water
$F_T = 1$

$$\frac{F_T U_{o,opt} H_y C_u}{c_{pu}(K_F C_{A_o} + E_{i,opt} H_y C_i + E_{o,opt} H_y C_o)}$$

$$= \frac{(1)(52)(7000)(5 \times 10^{-6})}{(1)\left[(0.2)(12)(1.15) + (4.1 \times 10^{-3})(80)^{3.5}(7000) \times \left(\frac{0.02}{2.655 \times 10^6}\right) + (3.8 \times 10^{-11})(640)^{1.75}(7000)\left(\frac{0.02}{2.655 \times 10^6}\right)\right]}$$

$$= 0.47$$

$$\frac{t_1' - t_2}{\Delta t_1} = \frac{150 - 100}{30} = 1.67$$

From Fig. 15-18,

$$\frac{\Delta t_{2,opt}}{\Delta t_1} = 1.4$$

$$\Delta t_{2,opt} = t_1' - t_{2,opt} = (30)(1.4) = 42°\text{F}$$

$$t_{2,opt} = 150 - 42 = 108°\text{F}$$

The assumption of $t_2 = 110°\text{F}$ is adequate.

Determination of optimum A_o:

$$\Delta t_{m,opt} = \frac{30 + 42}{2} = 36°\text{F}$$

$$A_{o,opt} = \frac{q}{U_{o,opt}\,\Delta t_{m,opt}} = \frac{(20{,}000)(0.25)(50)}{(52)(36)} = 134 \text{ sq ft}$$

From Fig. 15-16, the assumed purchased cost of \$12 per square foot of outside area is adequate.

Cost of installed exchanger = (134)(12)(1.15) = \$1850.

Determination of optimum number of tubes and tube length: From Eq. (*E*1) in Table 9,

$$G_{i,opt} = \left[\frac{(80)(0.782/12)^{0.2}(0.046)^{0.8}}{(0.023)(0.0162)}\left(\frac{0.0162}{0.25 \times 0.046}\right)^{1/3}\left(\frac{0.045}{0.046}\right)^{0.14}\right]^{1.25}$$

$$= 123{,}000 \text{ lb/(hr)(sq ft)}$$

$$S_{i,opt} = \frac{20{,}000}{123{,}000} = 0.163 \text{ sq ft}$$

$$\text{Number of tubes} = \frac{(4)(0.163)}{(3.14)(0.782/12)^2} = 49$$

$$\text{Tube length} = \frac{134}{(3.14)(1/12)(49)} = 10.5 \text{ ft}$$

A check on the Reynolds numbers indicates that flow on tube side and shell side is turbulent.

For the optimum exchanger:

Installed cost = \$1850

Number of tubes = 49

Tube length = 10.5 ft

NOTE: An optimum design of this type can be used as a guide for the final selection of an exchanger. However, practical factors of operation must also be considered. In this case, a large number of baffles are required to give the optimum conditions. Because the water-film coefficient is large relative to the air-film coefficient, a reduction in the number of baffles would have little effect on the optimum design.

SIMPLIFIED CASES OF OPTIMUM DESIGN

Immaterial Power Costs on Shell Side or Tube Side. In the operation of heat exchangers, the power cost for one of the fluids is often immaterial. For example, process cooling water is ordinarily supplied under sufficient pressure so that no pumping-power costs are necessary for the water. The highest useful water velocity should be employed in order to minimize the heat-transfer resistance caused by the water film, and a reasonable water-film coefficient can be assumed. Thus, if power costs on one side of the exchanger are immaterial, the problem reduces to one in which the film coefficient and, therefore, the fluid velocity on one side of the exchanger are fixed. Under these conditions, the number of independent variables for the development of the type of optimum design discussed in the preceding sections is two. Possible choices of the basic independent variables could be h_i, Δt_2; h_i, A_o; or A_o, Δt_2.*

Shell-side Power Cost Immaterial. In this case, the value of C_o in Eqs. (35) and (44) is zero and h_o is constant. The optimization can be accomplished by differentiating Eq. (44) under the given conditions. The following expression for the evaluation of $h_{i,opt}$ is obtained by setting the partial derivatives of Eq. (44) with respect to h_i and with respect to A_o equal to zero:

$$h_{i,opt}^{3.5}\left[2.5\psi_i H_y C_i + \frac{3.5\psi_i H_y C_i D_i}{D_o}\left(\frac{1}{h_o} + R_{dw}\right) h_{i,opt}\right] = K_F C_{A_o} \qquad (56)$$

The value of $h_{i,opt}$ can be determined from Eq. (56), and $U_{o,opt}$ can then be calculated from Eq. (38). When $U_{o,opt}$ is known, the optimum value of Δt_2 can be obtained from Eq. (48) or Fig. 15-18, and the optimum design is fixed.

Tube-side Power Cost Immaterial. Optimization of the heat-exchanger design for this situation is based on the assumption that C_i is zero and h_i is constant. The procedure is similar to that for the case of shell-side power immaterial as described in the preceding paragraph. The optimum value of h_o can be determined from the following equation, which is obtained by setting the partial derivatives of Eq. (44) with respect to h_o and with respect to A_o equal to zero:

$$h_{o,opt}^{4.75}\left[3.75\psi_o H_y C_o + 4.75\psi_o H_y C_o \left(\frac{D_o}{D_i h_i} + R_{dw}\right) h_{o,opt}\right] = K_F C_{A_o} \qquad (57)$$

If power costs on both the tube side and the shell side are to be considered, the ratio of these two costs can be evaluated from the following equation:

$$\frac{\text{Power cost on tube side}}{\text{Power cost on shell side}} = \frac{E_i C_i}{E_o C_o} = \frac{\psi_i h_i^{3.5} C_i}{\psi_o h_o^{4.75} C_o} \qquad (58)$$

As in the previous cases, Eq. (58) applies to a crossflow shell-and-tube exchanger with flow in the turbulent range and no phase change. The equation is not limited to optimum conditions.

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* An alternative approach for this type of situation is described in Chap. 9 (Optimum Design) for the case of optimum flow rate of cooling water in a condenser. Equation (54) in Chap. 9 is merely a special case of Eq. (48) where $t_1' - t_2'$ is zero.

Flow Rate of Utility Fluid Fixed. A situation sometimes occurs in which the maximum temperature of a utility coolant fluid is fixed, thereby setting the coolant flow rate. In other cases, the operating circumstances may arbitrarily set the utility-fluid flow rate as well as the process-fluid flow rate. Under these conditions, Δt_2 is constant, and only two independent variables are involved in the optimization procedure. Since Δt_2 was held constant in the development of Eqs. (45*c*), (46*b*), and (47), these equations can be used for determining the optimum over-all heat-transfer coefficient. This coefficient, combined with the known values of Δt_2 and Δt_1, is sufficient to permit calculation of the optimum heat-transfer area by Eq. (39), and the rest of the design variables are then established.

Change in Phase of One Fluid (Temperature of the Fluid Remains Constant). The procedure for developing an optimum heat-exchanger design is simplified if the temperature of one of the fluids remains constant. This condition is often encountered when one of the fluids changes phase, as in a condenser or a steam heater.

When the process fluid is the one that changes phase, the three independent variables h_i, h_o, and Δt_2 are involved, and the general procedure for developing the optimum-design equations is similar to that outlined for the case of no phase change.

Under many conditions, however, determination of the optimum over-all coefficient is simplified, because the pressure drop and the resulting power costs for a condensing fluid can be taken as zero and the heat-transfer resistance of the condensing-fluid film is relatively small, permitting the assumption of a reasonable constant value for the film coefficient. Thus, if the fluid that changes phase is the process fluid, the number of independent variables in the design is reduced to two, as in the case of immaterial power costs on the shell side or tube side. If the change in phase occurs on the shell side, Eq. (56) can be used to evaluate $h_{i,opt}$, and $U_{o,opt}$ can then be obtained from Eq. (38). Similarly, if the phase change is on the tube side, Eq. (57) gives the optimum value of h_o. When $U_{o,opt}$ is known, Eq. (48) with $t_1' - t_2'$ equal to zero, or the bottom line in Fig. 15-18, can be used to evaluate the optimum value of Δt_2. The procedure for this situation, as applied to a condenser with immaterial power costs for the utility fluid, is presented in detail in Chap. 9.

If the condensing fluid happens to be the utility fluid, as in a steam heater, the value of Δt_2 is set by the condensing temperature, and the independent variables are h_i and h_o. For the common case of negligible power cost and constant value of the film coefficient on the phase-change side of the exchanger, only one independent variable remains. In this situation, the optimum design can be established by setting the partial derivatives of Eq. (44) with respect to A_o and with respect to the independent film coefficient equal to zero. The resulting optimum film coefficient for change in shell-side phase can be calculated from Eq. (56), and that for change in tube-side phase is given by Eq. (57).

Velocity of One Fluid Fixed (h_i or h_o Fixed). Because of fouling effects, there may be a limit on the velocity of one of the fluids in a heat exchanger. For example, the velocity of cooling water in the tubes of a shell-and-tube exchanger is often specified as 3 fps. If the velocity of one fluid is specified, the coefficient for that fluid is set, and the independent variables become Δt_2 and the film coefficient of the other fluid.

Inside-tube Velocity Fixed. If the inside-tube velocity is fixed, h_i is constant, and the optimum value of h_o can be established by eliminating λ/A_o from Eqs. (45*b*) and (46*a*) to give

$$h_{o,opt}^{4.75}\left[3.75\psi_o H_y C_o + 4.75\psi_o H_y C_o\left(\frac{D_o}{D_i h_i} + R_{dw}\right)h_{o,opt}\right] = K_F C_{A_o} + \psi_i h_i^{3.5} H_y C_i \qquad (59)$$

Trial-and-error or graphical solution of Eq. (59) yields the value of $h_{o,opt}$, and $U_{o,opt}$ can be calculated from Eq. (39). Figure 15-18 or Eq. (48) can then be used to obtain $\Delta t_{2,opt}$, and the optimum design conditions are fixed.

Outside-tube Velocity Fixed. When h_o is constant, the procedure for evaluation of $h_{i,opt}$ and the other optimum conditions is similar to that described in the preceding paragraph. By eliminating λ/A_o from Eqs. (45*c*) and (46*a*), the following expression for evaluation of $h_{i,opt}$ is obtained:

$$h_{i,opt}^{3.5}\left[2.5\psi_i H_y C_i + \frac{3.5\psi_i H_y C_i D_i}{D_o}\left(\frac{1}{h_o} + R_{dw}\right)h_{i,opt}\right] = K_F C_{A_o} + \psi_o h_o^{4.75} H_y C_o \qquad (60)$$

GENERAL METHODS FOR PROCESS DESIGN OF HEAT EXCHANGERS

The procedures used for developing the design of heat exchangers vary with the type of problem and the preference of the worker. Some engineers prefer to develop the design for a heat exchanger by a method known as *rating an exchanger*. In this method, the engineer assumes the existence of an exchanger and makes calculations to determine if the exchanger would handle the process requirements under reasonable conditions. If not, a different exchanger is assumed, and the calculations are repeated until a suitable design is developed. For example, with a given set of process requirements, the engineer could assume the existence of an exchanger with a designated tube size, tube spacing, baffle type, baffle spacing, and number of tubes and passes. The engineer might then proceed through the process-design calculations by computing an over-all heat-transfer coefficient and evaluating all flow rates, areas, lengths, and pressure drops. Repeated trials may be necessary to obtain an accurate over-all coefficient. If the results of the final design indicate that the assumed exchanger has reasonable dimensions, reasonable cost, and acceptable pressure drops, the unit is considered as adequate and the design is complete.

An alternative approach, of course, is to base the design on optimum economic conditions, using the methods described in the preceding sections. No matter which approach is used, the general method of attack for a given set of process conditions consists of the following steps:

1. Determine the rates of flow and rate of heat transfer necessary to meet the given conditions.
2. Decide on the type of heat exchanger to be used, and indicate the basic equipment specifications.
3. Evaluate the over-all heat-transfer coefficient and also the film coefficients, if necessary. In many cases, fluid velocities must be determined in order to obtain accurate heat-transfer coefficients.
4. Evaluate the mean temperature-difference driving force.
5. Determine the necessary area of heat transfer and the exchanger dimensions.
6. Analyze the results to see if all dimensions, costs, pressure drops, and other design details are satisfactory.
7. If the results of (6) show that the exchanger is not satisfactory, the specifications given in (2) are inadequate. Choose new specifications and repeat steps 3 through 7 until a satisfactory design is obtained.

NOMENCLATURE FOR CHAP. 15

a_o = constant in Eq. (29) for evaluating outside film coefficient of heat transfer, dimensionless

A = area of heat transfer, sq ft; subscript m designates mean area; subscript o designates outside area; subscript f designates film area

b_o = constant in Eq. (32) for evaluating shell-side friction factor, dimensionless

B_i = correction factor in Eq. (30) to account for friction due to sudden contraction, sudden expansion, and reversal of flow direction, dimensionless

B_o = correction factor in Eq. (31) to account for friction due to reversal of flow direction, recrossing of tubes, and variation in cross section, dimensionless

c_c = constant, dimensionless; defined in Table 4

c_p = heat capacity, Btu/(lb)(°F); prime refers to process fluid

C_{A_o} = installed cost of heat exchanger per unit of outside-tube heat-transfer area, \$/sq ft

C_i = cost for supplying 1 ft-lb force to pump the fluid through the inside of the tubes, \$/ft-lb force

C_o = cost for supplying 1 ft-lb force to pump the fluid through the shell side of the exchanger, \$/ft-lb force

C_T = total annual variable cost for heat exchanger and its operation, \$/year

C_u = cost of utility fluid, \$/lb

D = diameter or distance, ft

D' = diameter, in.

D_c = clearance between tubes to give smallest free area across shell axis, ft

D_e = equivalent diameter = 4 × hydraulic radius, ft

E = power loss per unit of outside-tube heat-transfer area, ft-lb force/(hr)(sq ft); subscript i designates inside tubes, and subscript o designates outside tubes

f_i = Fanning friction factor for isothermal flow, dimensionless

f' = special friction factor for shell-side flow, dimensionless

F_A = correction factor for radiant heat transfer based on relative orientation of surfaces, dimensionless; defined by Eqs. (6) and (7)

F_c = friction due to sudden contraction, ft-lb force/lb mass

F_e = friction due to sudden enlargement, ft-lb force/lb mass

F_E = correction factor for radiant heat transfer based on emissivities and absorptivities of surfaces, dimensionless; defined by Eqs. (6) and (7)

F_r = friction due to reversal of flow direction, ft-lb force/lb mass

F_s = safety factor in Eq. (29) to account for bypassing on shell side of exchanger, dimensionless

F_T = correction factor on logarithmic-mean Δt for counterflow to give mean Δt, dimensionless; defined in Fig. 15-2

g = local gravitational acceleration, ft/(sec)(sec)

g_c = conversion factor in Newton's law of motion, 32.17 ft-lb mass/(sec)(sec)(lb force)

G = mass velocity inside tubes, lb/(hr)(sq ft)

G_s = shell-side mass velocity across tubes based on the minimum free area between baffles across the shell axis, lb/(hr)(sq ft)

h = film coefficient of heat transfer, Btu/(hr)(sq ft)(°F); subscript c indicates convection; subscript d represents dirt or fouling; subscript co indicates conduction

h_r = film coefficient for heat transfer by radiation, Btu/(hr)(sq ft)(°F)

H_y = hours of operation per year, hr/year

k = thermal conductivity, Btu/(hr)(sq ft)(°F/ft); subscripts x, y, and z refer to direction of heat-flow path

K = dimensional constant; defined in Table 4

K_c = constant in expression for evaluating friction due to sudden contraction, dimensionless

K_F = annual fixed charges including maintenance, expressed as a fraction of the initial cost for the completely installed unit, dimensionless

K_1 = constant for evaluation of B_i, dimensionless; defined with Eq. (30)

L = heated length of straight tube or length of heat-transfer surface, ft; if tubes in parallel are involved, L is the length of one tube

n = constant, dimensionless

n_b = number of baffle spaces = number of baffles plus 1, dimensionless

n_p = number of tube passes, dimensionless

N_c = number of clearances between tubes for flow of shell-side fluid across shell axis, dimensionless

N_{Gr} = Grashof number = $L^3\rho^2g\beta\ \Delta t/\mu^2$, dimensionless

N_{Pr} = Prandtl number = $c_p\mu/k$, dimensionless

N_r = number of rows of tubes across which shell fluid flows, dimensionless

N_{Re} = Reynolds number = DG/μ, dimensionless

N_t = total number of tubes in exchanger = number of tubes per pass × n_p, dimensionless

N_V = number of rows of tubes in a vertical tier, dimensionless
P, p = pressure, lb force/sq ft
q = rate of heat transfer, Btu/hr
Q = amount of heat transferred in time θ, Btu
r = radius, ft
R = temperature ratio for evaluating F_T, dimensionless; defined in Fig. 15-2
R_{dw} = combined resistance of tube wall and scaling or dirt factors, $[\text{Btu}/(\text{hr})(\text{sq ft})(°\text{F})]^{-1}$; defined with Eq. (39)
S = temperature ratio for evaluating F_T, dimensionless; defined in Fig. 15-2
S_H = cross-sectional flow area of header per pass, sq ft
S_i = cross-sectional flow area inside tubes per pass, sq ft
S_o = shell-side free-flow area across the shell axis, sq ft
t = temperature, °F; subscript b refers to average bulk temperature; subscript or refers to original temperature; subscript s refers to surface; in general, primes refer to the process fluid, subscript 1 refers to the entering temperature, and subscript 2 refers to the leaving temperature
t' = temperature of second fluid in a heat exchanger, °F; refers, in general, to process fluid
T = absolute temperature, °R
U = over-all coefficient of heat transfer, Btu/(hr)(sq ft)(°F); subscript d indicates that a dirt or fouling factor is included; subscript o indicates based on outside area and fouling factor included
V = velocity, ft/hr; subscript i indicates in tubes
V' = velocity, fps
w = weight rate of flow, lb/hr; no subscript indicates per tube; subscript u indicates total flow rate of utility fluid; subscript i indicates total flow rate of inside-tube fluid; subscript o indicates total flow rate of outside-tube fluid
w' = total weight rate of flow of process fluid, lb/hr
x = length of conduction path, ft
x_L = ratio of pitch parallel to flow to tube diameter, dimensionless
x_T = ratio of pitch transverse to flow to tube diameter, dimensionless
y = length of conduction path, ft
z = length of conduction path, ft

Greek Symbols

α = alpha, thermal diffusivity $= k/\rho c_p$, sq ft/hr
β = beta, coefficient of volumetric expansion, 1/°F
Δ = delta; Δt designates temperature-difference driving force, °F; subscript f designates across film; subscript m designates mean Δt; subscript oa or no subscript designates over-all Δt; $\Delta t_1 = t_2' - t_1$; $\Delta t_2 = t_1' - t_2$; ΔP and Δp designate pressure drop; $\Delta p = -\Delta P$
ϵ = epsilon, emissivity, dimensionless
θ = theta, time, hr
λ = lambda, latent heat of condensation, Btu/lb
ξ = Lagrangian multiplier, dimensionless; defined by Eq. (43)
μ = mu, absolute viscosity, lb/(hr)(ft)
π = pi, 3.1416$\cdots$
ρ = rho, density, lb/cu ft
σ = sigma, Stefan-Boltzmann dimensional constant for radiant heat transfer; defined by Eq. (5)

ϕ = phi, correction factor for nonisothermal flow, dimensionless; defined with Eq. (30)

ψ_i, ψ_o = psi, dimensional factors for evaluation of E_i and E_o; defined with Eqs. (40) and (41)

Subscripts

f = across film or at average film temperature
i = inside pipe or tube, based on average bulk temperature
L = liquid at average liquid temperature
m = mean
o = outside pipe or tube, based on average bulk temperature
oa = over-all
opt = optimum conditions
u = utility fluid
v = vapor at average vapor temperature
w = tube or pipe wall, based on temperature at wall surface

PROBLEMS

1. A single-pass shell-and-tube heat exchanger contains 60 steel tubes. The ID of the tubes is 0.732 in., and the OD is 1.0 in. The shell side of the exchanger contains saturated steam at 290°F, and water passes through the tubes. The unit is designed with sufficient tube area to permit 15,000 gph of water to be heated from 70 to 150°F. In the course of this design, an h_d of 1500 Btu/(hr)(sq ft)(°F) was assumed to allow for scaling on the water side of the tube. The film coefficient for the steam is 2000 Btu/(hr)(sq ft)(°F). No safety factor other than the one scale value was used in carrying out the exchanger design. Estimate the temperature of saturated steam which must be used when the exchanger is new (i.e., no scale present) if the water enters the unit at a rate of 15,000 gph and is heated from 70 to 150°F.

2. A horizontal heat exchanger has seven steel tubes enclosed in a shell having an ID of 5.0 in. The OD of the tubes is 1.0 in., and the tube wall thickness is 0.10 in. Pure ethyl alcohol flows through the 1.0-in.-OD tubes. The ethyl alcohol enters the unit at 150°F and leaves at 100°F. Water at 70°F enters the shell side of the unit and flows countercurrent to the ethyl alcohol. It is necessary to cool 50,000 lb of ethyl alcohol per hour, and it has been decided to use 100,000 lb of water per hour.

Under the following conditions, determine the total pumping cost for the two fluids in the exchanger as dollars per year:

(*a*) There are no baffles, and flow on shell side can be considered to be parallel to the tubes.

(*b*) The outside of the shell is insulated, and there is no heat loss from the shell.

(*c*) The unit operates three hundred 24-hr days per year.

(*d*) The efficiency of both pumps is 60 per cent.

(*e*) Contraction, expansion, and fitting losses can be accounted for by increasing the straight-section frictional pressure drop by 20 per cent.

(*f*) The specific heat of the ethyl alcohol may be assumed to be constant at 0.60. For water, the value may be assumed to be 1.0.

(*g*) The specific gravity of the ethyl alcohol may be assumed constant at 0.77. For water, the value may be assumed to be 1.0.

(*h*) No scale is present, and no safety factor is to be applied to the heat-transfer coefficients.

(*i*) Cost of power is $0.02 per kilowatthour.

3. A heat exchanger is to be constructed by forming copper tubing into a coil and placing it inside an insulated steel shell. If the following data apply, what should be the length of the coil?

(*a*) Water will flow inside the tubing, and a hydrocarbon vapor will condense on the outside of the tubing.

(*b*) ID of tubing = 0.5 in.
(*c*) OD of tubing = 0.6 in.
(*d*) Condensate rate = 1000 lb/hr.
(*e*) Temperature of condensation = 190°F.
(*f*) Heat of vaporization of hydrocarbon at 190°F = 144 Btu/lb.
(*g*) Heat-transfer coefficient for condensing vapor = 250 Btu/(hr)(sq ft)(°F).
(*h*) Inlet water temperature = 50°F.
(*i*) Outlet water temperature = 90°F.
(*j*) Heat losses from the shell may be neglected.

4. A solid surface at 1500°F is radiating to a second surface at 140°F. What temperature of the hot surface would be required if it were desired to double the number of Btu transmitted per hour, the sink temperature and both emissivities remaining constant? What will be the percentage increase of the radiation coefficient h_r under the changed conditions?

5. A plywood-manufacturing concern is using a binder that requires a temperature of 180°F in order to obtain adequate holding strength. Large slabs of the plywood at an initial uniform temperature of 70°F are placed in a heater, and the heating unit is maintained at a constant temperature. The manufacturer wishes to pass the slabs through the heater continuously at such a rate that each slab remains in the heater for 15 min. If the slabs are 1 in. thick, determine the minimum constant temperature (i.e., with negligible surface resistance) required for the heater if the temperature at the center of each slab is to reach 180°F before leaving the heater. The following average data apply to the plywood: density = 35 lb/cu ft; thermal conductivity = 0.10 Btu/(hr)(sq ft)(°F/ft); heat capacity = 0.50 Btu/(lb)(°F). Consider the plywood as homogeneous and isotropic.

6. A heat exchanger with two tube passes has been proposed for cooling distilled water from 93 to 85°F. The proposed unit contains 160 copper tubes, each $^{3}/_{4}$ in. OD, 18 BWG, and 16 ft long. The tubes are laid out on a $^{15}/_{16}$-in. triangular pitch, and the shell ID is $15^{1}/_{4}$ in. Twenty-five per cent cut segmental baffles spaced 1 ft apart are located in the shell. The correction factor F_s for use in evaluating the outside-tube film coefficient can be assumed to be 1.3. Cooling water at 75°F will be used to remove the heat, and this fluid will flow through the tubes at a velocity of 6.7 fps. Under these conditions, the fouling coefficient is 2000 Btu/(hr)(sq ft)(°F) for the distilled water and 1000 Btu/(hr)(sq ft)(°F) for the cooling water. The pressure drop on the tube side and on the shell side cannot exceed 10 psi. Would the proposed unit be satisfactory for cooling 175,000 lb of distilled water per hour?

7. Determine the installed cost, tube length, and number of tubes for the optimum exchanger that will meet the following operating conditions and specifications:

(*a*) Twenty thousand pounds of air per hour is cooled from 150 to 100°F inside the tubes of a shell-and-tube exchanger.

(*b*) Water is used as the cooling medium. The water enters the unit at 70°F and leaves at 100°F.

(*c*) All other conditions are the same as those specified in Example 5 of this chapter, except that B_i is not given.

8. Present a detailed derivation of Eq. (48) in this chapter, using, as a starting point, any of the other equations that are given.

9. Air, for use in a catalytic oxidation process, is to be heated from 200 to 520°F before entering the oxidation chamber. The heating is accomplished by the product gases, which cool from 720 to 400°F. A steel one-pass shell-and-tube exchanger with crossflow on the shell side will be used. The average absolute pressure on both the shell side and tube side can be assumed to be 10 atm, and the hot gases will pass through the tubes. The exchanger must handle 15,000 lb of the colder gas per hour, and it operates continuously for 8000 hr/year. The properties of the product gases can be considered as identical to air. The cost for power delivered to either gas is \$0.02 per kilowatthour. The OD of the tubes is 1.0 in.; the ID is 0.782 in. The tubes will be arranged in line with a square pitch of 1.5 in. All thermal resistances except those of the gas films may be neglected. The safety factor F_s for the outside film coefficient is 1.4. The terms B_o/n_b and N_rN_c/N_t can both be assumed to be equal to 1.0. The cost data presented in Fig. 15-16 apply. Installation costs are 15 per cent of the purchased cost, and annual fixed charges including maintenance are 20 per cent of the installed cost. Under these conditions, estimate the tube length and purchased cost for the optimum exchanger.

CHAPTER 16

MASS-TRANSFER EQUIPMENT—DESIGN AND COSTS

The transfer of mass from one phase to another is involved in the operations of distillation, absorption, extraction, humidification, adsorption, drying, and crystallization. The principal function of the equipment used for these operations is to permit efficient contact between the phases. Many special types of equipment have been developed that are particularly applicable for use with a given operation, but finite-stage contactors and continuous contactors are the types most commonly encountered. The major part of this chapter, therefore, is devoted to the design aspects of stagewise plate contactors and continuous packed contactors.

The initial cost for the operating equipment includes expenses for foundations, supports, installation, shell and shell internals, insulation, pumps, blowers, piping, heaters, coolers, and other auxiliaries, such as instruments, controls, heat exchangers, or special accessory equipment. Operating costs include power for circulating the fluids, maintenance, labor, cooling water, steam, and unrecovered materials. As illustrated in Chap. 9, a balance can be made among these various costs to yield an optimum economic design.

FINITE-STAGE AND DIFFERENTIAL-STAGE CONTACTORS

Because the equipment for a finite-stage contactor consists of a series of interconnected individual units or stages, a study of the over-all assembly is best made on the basis of the flow and mass-transfer characteristics in each individual stage. Thus, for a bubble-cap contactor, each tray can be considered as a separate entity, and the total design requires an analysis of the stepwise operation from one tray to another. In a differential-stage contactor, such as a packed column, the contacting operation can be considered as occurring continuously throughout the unit, since there are no locations where the equipment is divided physically into finite sections. The over-all analysis for a differential-stage contactor, therefore, can be based on a differential length or height.

Mass transfer between two phases can occur when there is a driving force, such as a concentration difference, between the phases. When equilibrium conditions are attained, the driving force and, consequently, the net rate of mass transfer becomes zero. A state of equilibrium, therefore, represents a theoretical limit for mass-transfer operations. This theoretical limit is used extensively in mass-transfer calculations.

A theoretical stage is defined as a contacting stage in which equilibrium is attained between the various phases involved. Thus, in a bubble-cap column, a theoretical or perfect plate is one in which the liquid leaving the tray is in equilibrium with the gas leaving the tray. The same approach is often used for packed columns, where the HETP is defined as the height of the packed column necessary to give a separation equivalent to one theoretical plate. A more rigorous method for evaluating the performance of a continuous contactor requires a differential treatment of the separating process and gives results that can be expressed in terms of the mass-transfer coefficient or as the number of transfer units. The transfer unit is similar to the theoretical plate, but the transfer unit is based on a differential change in equilibrium conditions and actual concentrations, and the theoretical plate is based on finite changes.

The design of most mass-transfer equipment requires evaluation of the number of theoretical stages or transfer units. Methods for carrying out these calculations for various types of mass-transfer operations are presented in many general chemical engineering books. The following list indicates recommended texts on this subject:

Badger, W. L., and J. T. Banchero: "Introduction to Chemical Engineering," McGraw-Hill Book Company, Inc., New York, 1955.

Brown, G. G., et al.: "Unit Operations," John Wiley & Sons, Inc., New York, 1950.

Coulson, J. M., and J. F. Richardson: "Chemical Engineering," vol. II, McGraw-Hill Book Company, Inc., New York, 1956.

McCabe, W. L., and J. C. Smith: "Unit Operations of Chemical Engineering," McGraw-Hill Book Company, Inc., New York, 1956.

Robinson, C. S., and E. R. Gilliland: "Elements of Fractional Distillation," 4th ed., McGraw-Hill Book Company, Inc., New York, 1950.

Sherwood, T. K., and R. L. Pigford: "Absorption and Extraction," 2d ed., McGraw-Hill Book Company, Inc., New York, 1952.

Treybal, R. E.: "Liquid Extraction," McGraw-Hill Book Company, Inc., New York, 1951.

Treybal, R. E.: "Mass-transfer Operations," McGraw-Hill Book Company, Inc., New York, 1955.

Because methods for determining theoretical stages and transfer units are covered extensively in the preceding references, the details will not be repeated here. Other important decisions, however, must be made in the design of mass-transfer equipment, and an error in these decisions can be just as detrimental as an error in evaluating the number of theoretical stages. The following sections deal with design factors for finite-stage and differential-stage contactors as related to the direct operational characteristics of the equipment.

FINITE-STAGE CONTACTORS

The most common type of finite-stage contactor is the bubble-cap plate unit, although sieve plates, turbogrid trays, cascade towers, and other specialty types of units are also used in industrial operations. Many of the principles that apply to bubble-cap units are also applicable to the other types of finite-stage contactors. For this reason, the bubble-cap plate unit will be discussed first.

Bubble-cap Towers

A bubble-cap tower, as illustrated in Fig. 16-1, consists of a series of trays, each equipped with a number of individual bubble-cap assemblies.

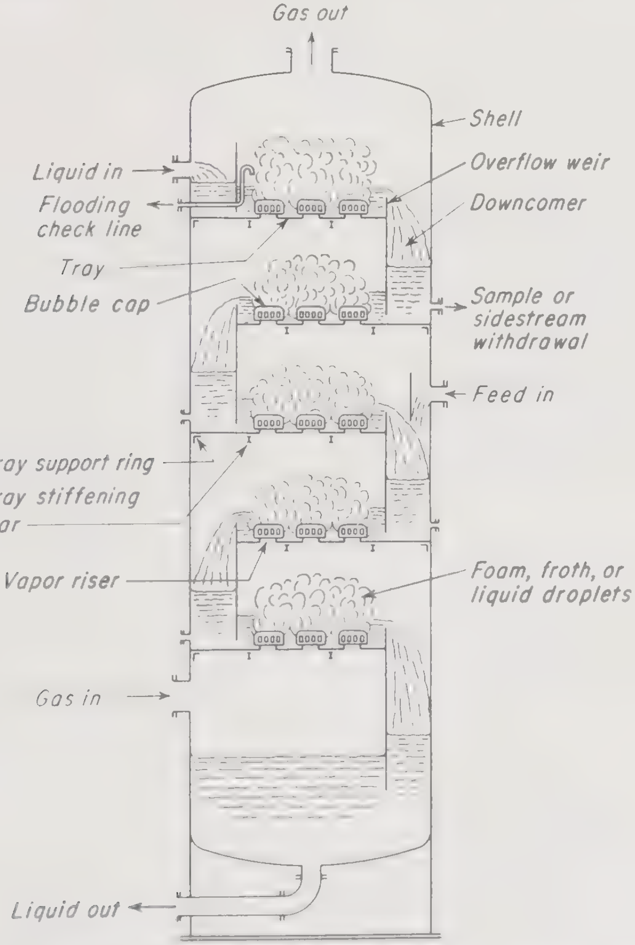

FIG. 16-1. Cross-sectional view of bubble-cap tray tower in operation.

These units are commonly employed for achieving mass transfer between a gas phase and a liquid phase and are used extensively in both rectification and absorption operations. The gas passes upward through the risers into the bubble caps, where the liquid level is depressed, permitting the gas to bubble through the slots or notches in the cap into the liquid. As the bubbles are dispersed into and rise through the liquid on the tray, a large amount of interfacial area exists between the gas and liquid phases, thereby permitting effective mass transfer. Liquid flows downward from tray to tray through downspouts, and the necessary gas-liquid contact is made as the liquid passes across each tray.

Caps and Risers. Figures 16-2 to 16-4 illustrate typical examples of bubble caps and risers. Round bell caps are commonly used with diameters ranging from 4 to 7 in. A 6-in.-diameter cap with a 4-in.-diameter riser is a standard size used in many industrial operations. Cap diameters as large as 8 in. have been employed successfully in some operations, and 3-in. caps with 2-in. risers are used in many vacuum towers. Tunnel caps are ordinarily 3 to 6 in. wide and 12 or more in. long. Comparison of the two types shows that tunnel caps have the advantage of a smaller number of units for installation for a given slot and riser area, but the round caps are more adaptable to changes in tray layout and can be purchased and stocked in one standard size.

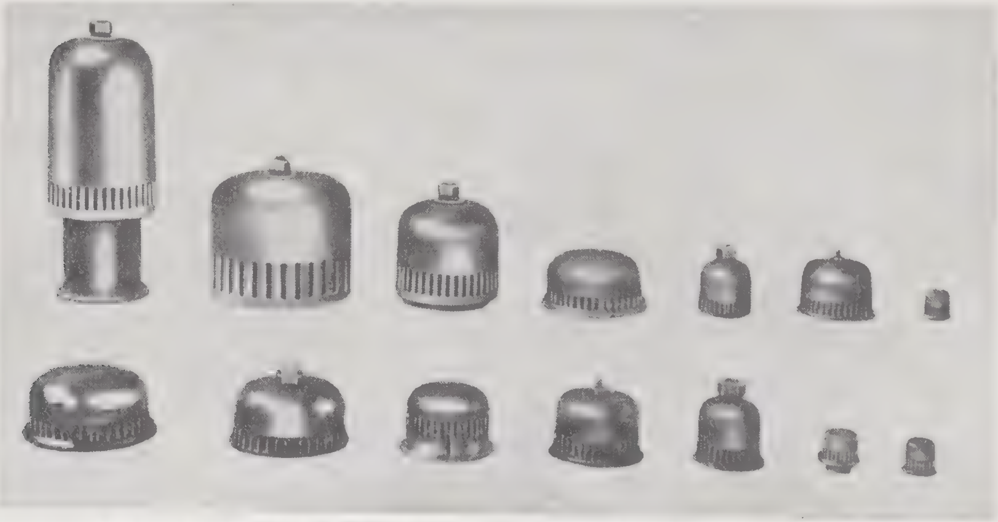

FIG. 16-2. Bubble caps and risers. (*Badger Manufacturing Company.*)

The caps are slotted around the lower periphery and can be anchored to the plate with teeth touching the plate or suspended to permit a so-called "skirt clearance" between the plate and the cap. Slots can be of a sawtooth type or in the form of punched holes, usually rectangular or triangular. In common practice, a skirt clearance in the range of 0.5 to 1.5 in. is

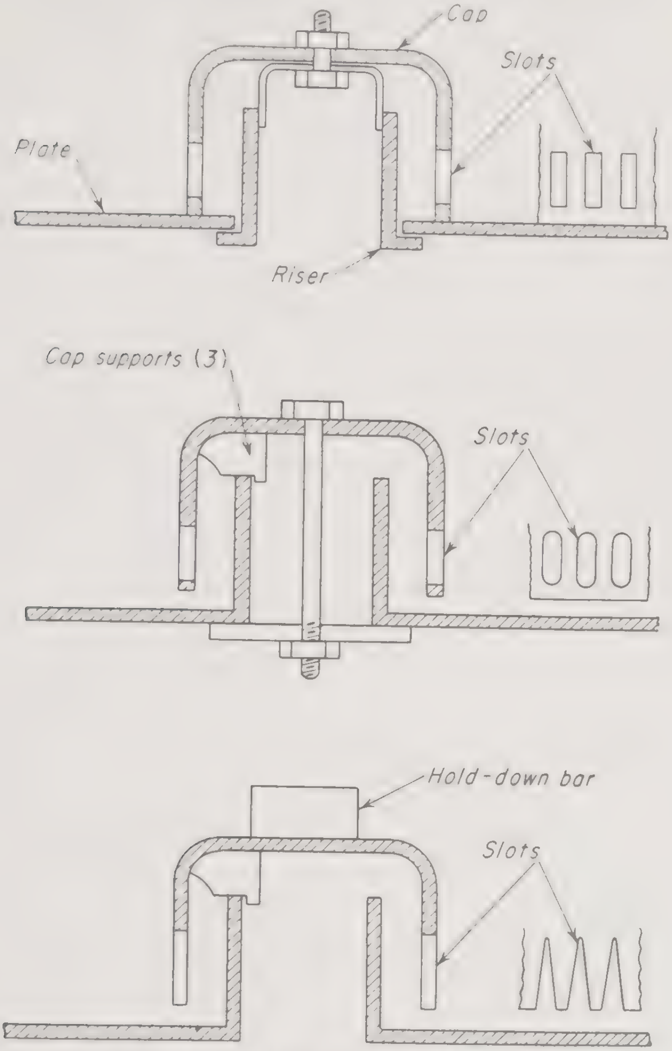

FIG. 16-3. Methods for holding bubble caps in place.

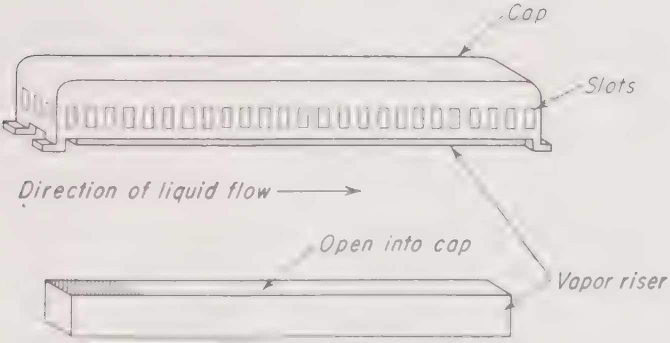

FIG. 16-4. Tunnel cap.

recommended to prevent plugging of the slots by residue build-up. Since the purpose of the slots is to disperse the gas into the liquid in the form of small bubbles, sufficient slot area should be provided in order that no gas may pass through the skirt clearance.

As illustrated in Fig. 16-3, the caps can be held in place by bolts or by a hold-down bar; however, the hold-down bar is seldom used because it interferes with the flow distribution. Since periodic removal or maintenance of the caps may be necessary, the preferred method for holding caps and trays in place permits removal of the caps by one man working in the crawl space above the plate.

Slot Velocities and Relative Dimensions. After the design of the cap has been established, the next step is to determine the number of bubble caps to be used per tray. This number is set by the allowable gas velocity through the slots. If the velocity is too high, pressure drop may be excessive and the liquid may be blown away from the cap, thus resulting in poor efficiency. On the other hand, if the velocity is too low, the gas bubbles will have little opportunity to disperse through the liquid, and the efficiency of the tray will be low. Davies has recommended the following equations for use in preliminary estimates of slot velocities in rectification columns: *

$$\text{Maximum linear slot velocity, fps} = \frac{12}{\rho_G^{0.5}} \tag{1}$$

$$\text{Minimum linear slot velocity, fps} = \frac{3.4}{\rho_G^{0.5}} \tag{2}$$

where ρ_G = gas density, lb/cu ft.

In common design practice, the riser area, total slot area, and passage area in the annular space under the cap are approximately equal in order to reduce pressure losses caused by expansion and contraction. Gas bubbles issuing from the slots are seldom projected more than about 1 in. from the cap, and a clearance between caps in the range of 1 to 3 in. is usually sufficient to eliminate large amounts of undesirable bubble coalescence. The caps should be spaced evenly over the entire tray. A clearance between the shell and adjacent caps of less than 2 in. is recommended in order to reduce the possibility of liquid bypassing the bubble-contact regions. For towers 3 or more feet in diameter, a plate layout with the total riser area in the range of 10 to 20 per cent of the tower cross-sectional area is common, with the greater riser area being more easily obtainable in larger-diameter towers.

Shell and Trays. Cylindrical shells are commonly used for bubble-cap columns. The shell may be constructed of short sections that are bolted together or in the form of one long cylinder. Manholes should be provided to give access to the individual trays for cleaning, maintenance, and installation. Adequate foundations and tower supports must be provided. In general, the size of the foundations is set by the size necessary to resist the overturning stresses on the column, since this load usually exceeds the direct load caused by the weight of the column assembly.

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* J. A. Davies, *Petroleum Refiner*, **29**(9):121 (1950).

Both the corrosion characteristics of the fluids involved and costs dictate the acceptable materials of construction for the shell and trays. Bubble caps and trays are usually made of a suitable metal to facilitate fabrication, but the shell material can be glass, plastic, impervious carbon, wood, glass-lined or resin-lined steel, or metal. Despite the additional weight involved, trays are often made of cast iron, usually 0.5 in. thick. With cast-iron trays, the risers may be fabricated as a permanent part of the tray. Lighter-gauge alloy metals may be cheaper than cast iron, and the final decision must be made on the basis of the situation for each individual case.

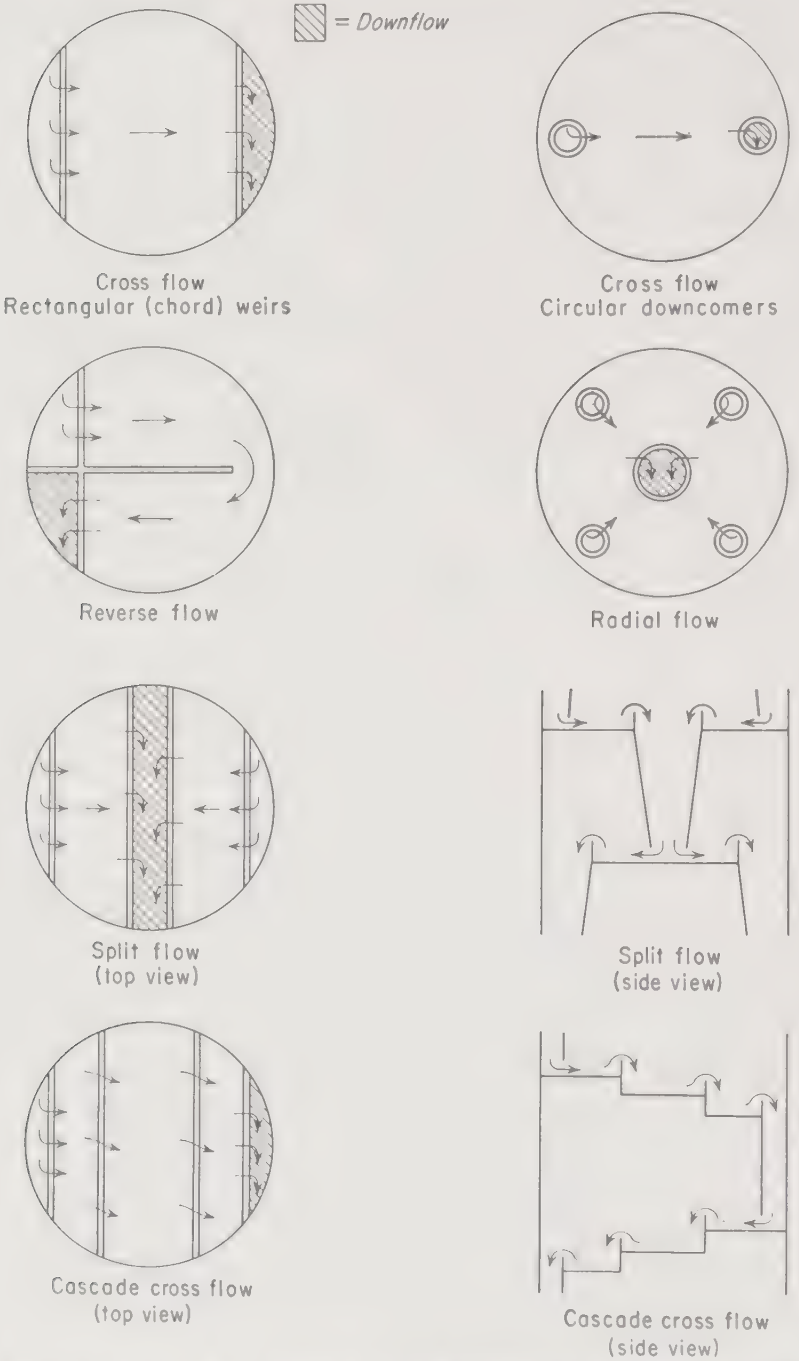
Supporting beams are used to stiffen the trays, and the trays must be fastened securely to prevent movement caused by gas surges. To allow for thermal expansion and to facilitate installation, slotted boltholes should be provided in the supporting rings, and there should be adequate clearance between the tray and shell wall.

Tray Level. The calculations for bubble-cap trays are based on the assumption that the trays are perfectly level. A tolerance of $\pm\frac{1}{8}$ in. change in vertical tray level is usually specified for the location of tray supports and fastening of the trays to these supports. Variations from the horizontal level are also caused by foundation settling, tray deflections caused by operating conditions, tower deflection due to wind loads, and uneven corrosion of the tray or tray supports. For design purposes, a maximum change in tray level of $\frac{1}{2}$ in. is a safe assumption, and this figure can be used as a safety factor in setting the seal dimensions of the tray.

Leakage and Weep Holes. To ensure a minimum of liquid leakage from one tray to another, the risers should be fitted firmly or sealed into the trays, and an effective seal is necessary around the tray supports. In large columns, the trays are often made in sections for ease of installation. Each of these sections must be installed carefully to minimize leakage.

Provision for draining the liquid from a tray when the unit is not in operation is made by the use of *weep holes.* These holes are usually located near the overflow weir so that any delivery during operation follows approximately the same path as the overflow fluid. The weep holes must be large enough to prevent plugging, but they should not deliver an excessive amount of fluid during operation. A size in the range of $\frac{1}{4}$- to $\frac{5}{8}$-in. diameter is usually adequate.

Liquid Flow. High tray efficiency is achieved when all the bubble caps are delivering uniformly into liquid that is evenly distributed over the entire tray surface. The beneficial effects of liquid concentration gradient



Cross flow
Rectangular (chord) weirs

Cross flow
Circular downcomers

Reverse flow

Radial flow

Split flow
(top view)

Split flow
(side view)

Cascade cross flow
(top view)

Cascade cross flow
(side view)

Fig. 16-5. Liquid flow patterns for different types of bubble-cap trays.

are obtained if liquid crossflow is used, where the liquid enters on one side of the tray and makes one pass across the tray. For tower diameters larger than 4 ft, better liquid distribution and less change in liquid head can often be achieved by using split flow, radial flow, or cascade flow, as illustrated in Fig. 16-5.

Because of the flow resistance of the caps and risers, there is a decrease in liquid depth as the liquid passes across the tray. Figure 16-6 shows an extreme example in which this liquid gradient is so great that only one out of the four bubble caps is operating normally. In general, the dimensionless ratio of total liquid gradient to pressure-drop head caused by the bubble-cap assembly should be less than 0.4 in order to ensure adequate vapor distribution, and, for single-pass crossflow trays, the rate of liquid flow across the tray should be less than 0.22 cu ft/(sec)(ft diameter).

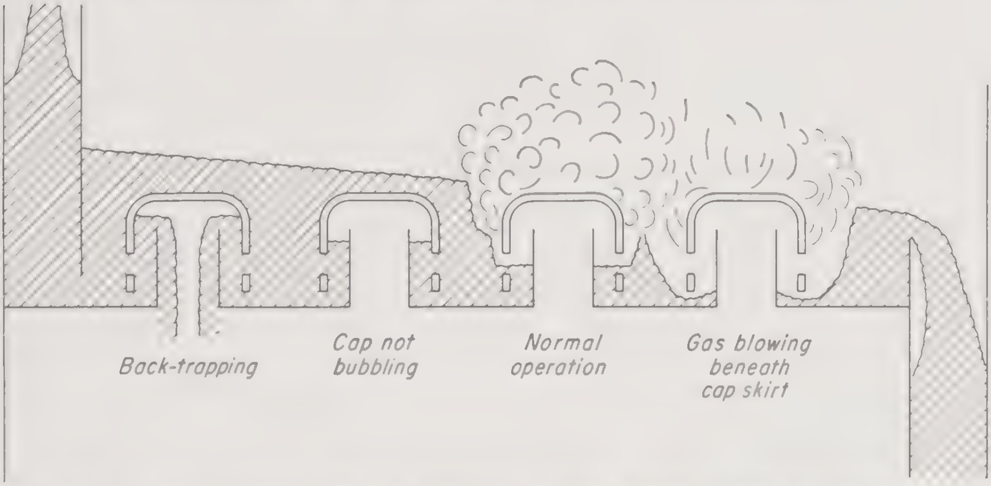


Fig. 16-6. Cross-sectional view of bubble-cap tower showing effect of excessive liquid gradient.

A total liquid gradient of 0.5 in. over one tray is usually acceptable, but a different flow pattern should be considered if the value approaches 1 in. The liquid gradient can be reduced by decreasing the number of rows of caps through which the liquid flows or by decreasing the velocity of liquid flow past the caps. A higher skirt clearance or a higher weir will sometimes be sufficient to reduce excessive liquid gradients to acceptable values.

Entrainment. As a gas passes through the bubble-cap slots into the liquid, a large amount of turbulence is set up, and liquid particles can become entrained with the gas. Carry-over of these liquid particles from one tray to the tray above is known as *entrainment*. It is often defined as the weight of liquid entrained per unit weight of gas. Liquid can be entrained by the gas as a result of violent splashing of the liquid or because of extensive foaming or frothing.

Entrainment has an adverse effect on the column operation in that it reduces the concentration change per tray and, consequently, decreases the efficiency. Nonvolatile impurities can be carried up a tower by entrainment, resulting in off-color or impure overhead products.

The major factors that determine the amount of entrainment are plate spacing, depth of liquid above the bubble-cap slots, and vapor velocity in the volume between the plates. Slot vapor velocity and liquid flow rate have some effect on the entrainment, but they are not of major importance.

Tray Spacing. Tray spacing in large columns is usually determined by the need for easy access for maintenance and inspection. With columns less than 3 ft in diameter, the minimum value of tray spacings is about 6 in., and greater values are used in most cases. In the petroleum industry, an 18-in. spacing is considered to be the minimum value below which entrainment or tendency toward flooding becomes excessive, and a tray spacing of 20 to 24 in. is often set as a minimum for reasons of accessibility. Table 1 presents recommended tray spacings for petroleum rectification columns of various diameters.

TABLE 1. RECOMMENDED TRAY SPACINGS FOR BUBBLE-CAP TOWERS

Tower diameter, ft	*Tray spacing, in.*
	6 minimum
4 or less	18–20 (no manways in trays)
6–10	24
12–24	36

Downcomers and Weirs. Downcomers for conducting the liquid from one tray to the next tray below may be in the form of circular pipes or segments of the tower isolated from the rising gas by means of vertical or angled plates. Some vapor is entrained in the liquid as the liquid enters the downcomer, and sufficient residence time should be provided in the downcomer to permit escape of the entrained vapor. A residence time of 5 sec, evaluated as the volume of the downcomer divided by the volumetric flow rate of the downcoming fluid, is enough to permit release of most of the entrained vapor. Vapor release is also accomplished by providing a calming section before the liquid flows into the downcomer. This is supplied by locating the caps 3 to 5 in. from the downcomer weir or by blanking off the cap slots that face toward the downcomer. The liquid head in the downcomer should not be greater than one-half the plate spacing.

The discharge end of the downcomer must project far enough into the tray liquid so that no gas bubbles can enter the open end and bypass the bubble caps. When the liquid contains no sediment, a seal pot or discharge weir is often placed around the discharge end of the downcomer to make certain that no free vapor can enter the open end. The distance between the liquid level on the loaded discharge plate and the bottom of the downcomer when no liquid is flowing is known as the *downcomer liquid seal*. A downcomer liquid seal, based on a perfectly level tray, in the range of ½ to 1½ in. is usually satisfactory.

An extension of the downcomer plate can be used as an overflow entrance weir, or a separate overflow weir may be provided. Since adequate vapor-disengaging space is necessary, extension of circular-pipe downcomers to form an overflow weir is not recommended if the column diameter is greater than 3 ft. Straight rectangular weirs are often used, and, on crossflow trays, they generally have a length in the range of 0.6 to 0.8 times the column diameter.

The height of the overflow weir is a major factor in determining the head of liquid over the bubble-cap slots. Although plate efficiency is increased slightly as the liquid head over the slots is increased, the beneficial effect is seldom enough to counterbalance the detrimental pressure-drop effects caused by high heads. This is particularly true when pressure drop is an important factor, as with towers operating under vacuum. The distance between the top of the slots and the liquid surface when the static liquid is just ready to flow over the overflow weir is known as the *static submergence*. Table 2 shows recommended values of static submergence for various operating pressures.*

TABLE 2. TYPICAL VALUES OF STATIC SUBMERGENCE FOR BUBBLE-CAP PLATE COLUMNS

Operating pressure	*Static submergence, in.*
Vacuum (30 mm Hg abs.)	0
Atmospheric	½
100 psig	1
300 psig	1½
500 psig	1½

Example 1. Determination of Holdup Time in Downcomer. A bubble-cap tower with 24-in. plate spacing and liquid crossflow contains straight segmental downcomers. The overflow weir at the downcomer entrance is formed by an extension of the downcomer plate. The height of this weir is 3 in. The inside diameter D of the tower is 5 ft, and the weir length is $0.6D$. If liquid with a density of 55 lb/cu ft flows across the plate at a rate of 30,000 lb/hr, estimate the residence or holdup time in the downcomer from this plate.

Solution

Volumetric flow rate of downcoming fluid = $30{,}000/(55)(3600) = 0.152$ cfs

Weir length = $l_w = (0.6)(5) = 3$ ft

Perpendicular distance from weir to center of tower = $d_{wc} = [(D/2)^2 - (l_w/2)^2]^{1/2} = [(5/2)^2 - (3/2)^2]^{1/2} = 2$ ft

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* J. A. Davies, *Petroleum Refiner*, **29**(9):121 (1950).

If θ designates the angle in degrees subtended from the center of the tower by the weir,

$$l_w = D \sin \frac{\theta}{2}$$

$$\sin \frac{\theta}{2} = 0.6$$

$$\theta = 73.7°$$

Downcomer cross-sectional area is

$$\frac{\pi D^2 \theta}{1440} - \frac{l_w d_{wc}}{2} = \frac{(3.14)(5)^2(73.7)}{1440} - \frac{(3)(2)}{2} = 1.02 \text{ sq ft}$$

Alternatively, downcomer cross-sectional area is

$$\frac{\pi D^2}{8} - \frac{l_w d_{wc}}{2} - \frac{D^2}{4}\left(\sin^{-1}\frac{2d_{wc}}{D}\right)_{\text{radians}} = 1.02 \text{ sq ft}$$

$$\text{Effective height of downcomer} = \frac{24+3}{12} = 2.25 \text{ ft}$$

$$\text{Residence time} = \frac{\text{volume of downcomer}}{\text{volumetric flow rate of downcoming fluid}}$$

$$= \frac{(2.25)(1.02)}{0.152} = 15 \text{ sec}$$

NOTE: The preceding answer is based on the assumption that the descending liquid occupies all the available volume in the downcomer.

Plate Stability. The term *plate stability* refers to the ability of the plate to maintain satisfactory operating characteristics when flow rates change or when unsteady-state conditions exist. Vapor and liquid distribution on the plate are the primary factors that determine plate stability. A stable plate is one in which all the caps are bubbling, and the best efficiencies are obtained when the vapor flow is evenly distributed among the caps. Thus, an ideal plate would have all the caps discharging uniformly, even when fluctuations in flow rates occur. In an actual column, the vapor is not distributed uniformly among the caps primarily because of the gradient in liquid height across the tray.

The following rules can be used as a guide for designing a tray to give stable operation and reasonably even vapor distribution:

1. The pressure drop caused by the caps and slots and the static submergence should be as high as practicable for reasonable operation.
2. The liquid gradient across the tray should be about 0.5 in. and no more than 1 in.
3. The dimensionless ratio of liquid gradient to pressure-drop head caused by the bubble-cap assemblies should be less than 0.4.
4. Tendency toward stable operation is increased by increasing the skirt

clearance of the caps, lowering the rate of liquid flow per foot of plate width, or increasing the spacing between caps.

Pressure Drop. As the gas passes through a bubble-cap plate, the pressure of the gas decreases because of the following causes:

1. Pressure drop through cap assembly
   - *a.* Contraction as the gas enters the riser
   - *b.* Friction in the riser and annular space of cap
   - *c.* Friction due to change in direction of gas flow
   - *d.* Passage of the gas through the slots
2. Pressure drop due to liquid head above slots

Because the pressure is uniform throughout the gas space above or below a tray, the gas pressure drop across a given tray must be the same no matter what location on the tray is considered. A design estimate of the pressure drop, therefore, can be obtained on the basis of an average bubble-cap assembly. Because of the liquid gradient, the volumetric flow rate of gas through the individual caps varies from the liquid-inlet to the liquid-outlet location on the tray. For a stable plate, an average bubble-cap assembly for use in pressure-drop calculations is one located at the point of average liquid gradient. The flow rate of gas through this cap can then be assumed to be the flow rate per cap, assuming each cap on the tray delivers the same amount of gas.

Pressure Drop through Cap Assembly. A cross-sectional view of an average bubble cap is shown in Fig. 16-7. Causes for pressure drop through the riser and cap are shown in this figure as (1) contraction, (2) friction in riser, (3) reversal of flow direction, and (4) friction in annular space. The total pressure drop due to the preceding causes is primarily a function of the kinetic head. The pressure drop as feet of liquid equivalent to one kinetic head is

$$h_H = \frac{V_c^2}{2g} \frac{\rho_G}{\rho_L} \tag{3}$$

where V_c = maximum linear velocity of gas in riser, reversal area, or annulus, fps

ρ_G = gas density, lb/cu ft

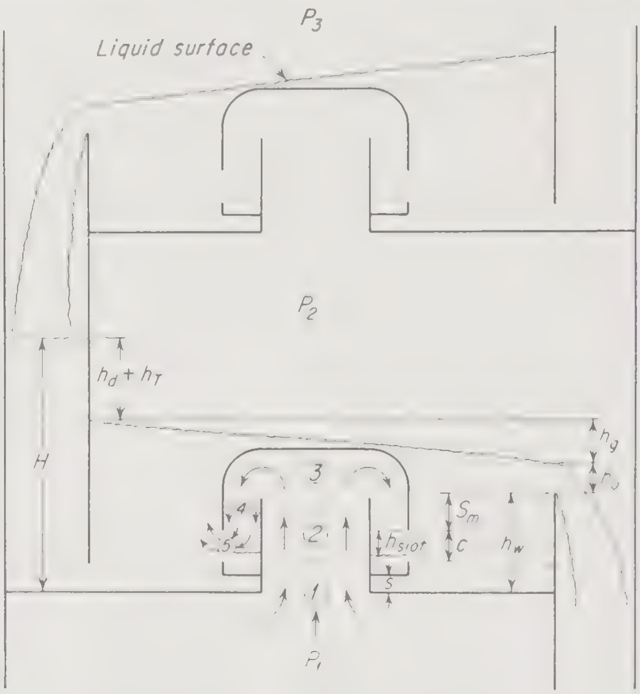
ρ_L = density of clear (unaerated) liquid, lb/cu ft

g = local acceleration due to gravity, ft/(sec)(sec)

The total pressure drop through the riser and cap is usually in the range of four to eight kinetic heads, depending on the cap design. A factor of six kinetic heads is a reasonable average figure. With this factor, the pressure drop due to gas flow through the riser and cap expressed as liquid head is

$$h_c = \frac{3V_c^2}{g} \frac{\rho_G}{\rho_L} \tag{4}$$

Pressure drop through the slots is a direct function of the vertical distance the liquid is depressed below the top of the slots. In Fig. 16-7, this distance is represented by h_{slot}. The difference in pressure between the inside of the cap and the liquid outside the cap at the top of the slots is defined as the pressure drop through the slots. Consequently, h_{slot} is the liquid head equivalent to the pressure drop through the slots.



h_d = head equivalent to liquid pressure drop through downcomer and constriction

h_c = head equivalent to gas pressure drop through riser and cap

h_{slot} = head equivalent to gas pressure drop through slots

$h_T = P_1 - P_2 = h_c + h_{slot} + S_m + h_o + h_g/2 \cong P_2 - P_3$

$H = h_w + h_o + h_g + h_d + h_T$

FIG. 16-7. Cross-sectional view of bubble-cap tower showing flow and nomenclature for pressure-drop calculations. (Units of all symbols are feet of liquid.)

At low gas velocities, intermittent bubbling through the slots is obtained because of liquid surface-tension effects, and the pressure drop is a function of the surface tension and the slot dimensions. When the velocity increases sufficiently, the gas issues from the slots in a steady stream, and the effect of surface tension becomes unimportant.

Under normal operating conditions, the slots remain partly open continuously and the gas is delivered in a steady stream. For this situation, the following equations, developed by Cross and Ryder,* can be used to estimate the average slot opening and the pressure drop through the slots: †

For rectangular-shaped slots

$$h_{\text{slot}} = 1.5 \left(\frac{Q_s}{b}\right)^{2/3} \left[\frac{\rho_G}{(\rho_L - \rho_G)g}\right]^{1/3} \tag{5}$$

For triangular-shaped slots

$$h_{\text{slot}} = 1.85 \left(\frac{cQ_s}{b}\right)^{2/5} \left[\frac{\rho_G}{(\rho_L - \rho_G)g}\right]^{1/5} \tag{6}$$

where Q_s = volumetric flow rate of gas per slot, cfs
b = width of slot at base, ft
c = height of slot, ft

Equations (5) and (6) apply when h_{slot} is less than c, and a design value for h_{slot} of $0.5c$ is often recommended.

Pressure Drop Due to Liquid Head above Slots. Reference to Fig. 16-7 shows that the total head above the slots for an average cap is the sum of static submergence S_m, height of liquid crest above weir h_{ow}, and average

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* C. A. Cross and H. Ryder, *J. Appl. Chem.*, **2**:51 (1952). Results identical to Eqs. (5) and (6), except for a slight change in the constants, have been presented by M. C. Rogers and E. W. Thiele, *Ind. Eng. Chem.*, **26**:524 (1934).

† According to Cross and Ryder, the surface tension and density of the liquid and the cap geometry determine the value of h_{slot} if Q_s is less than a critical value. For rectangular-shaped slots, the following dimensional equation applies for h_{slot} when Q_s is less than $(\alpha_s/\beta_s)^{3/2}$:

$$h_{\text{slot}} = \alpha_s$$

where $$\alpha_s = 6.9 \times 10^{-5} \frac{\sigma}{b\rho_L} + \left[4.7 \times 10^{-9} \left(\frac{\sigma}{b\rho_L}\right)^2 + 1.4 \times 10^{-4} \frac{\sigma}{\rho_L}\right]^{1/2}$$

$$\beta_s = 1.5 \left(\frac{1}{b}\right)^{2/3} \left[\frac{\rho_G}{(\rho_L - \rho_G)g}\right]^{1/3}$$

For triangular-shaped slots, the following dimensional equation applies for h_{slot} when Q_s is less than $(\alpha_s'/\beta_s')^{5/2}$:

$$h_{\text{slot}} = \alpha_s'$$

where $$\alpha_s' = 0.0116 \left[\frac{\sigma}{\rho_L}\left(\frac{2c}{b} + 1\right)\right]^{1/2}$$

$$\beta_s' = 1.85 \left(\frac{c}{b}\right)^{2/5} \left[\frac{\rho_G}{(\rho_L - \rho_G)g}\right]^{1/5}$$

σ = surface tension of liquid, dynes/cm

Units of h_{slot}, c, and b are feet. Units of ρ_G and ρ_L are pounds per cubic foot. Units of Q_s are cubic feet per second. Units of g are ft/(sec)(sec).

liquid gradient $0.5h_g$. The static submergence is determined directly by the construction details of the plate, and design methods are available for estimating the liquid crest over the weir and the liquid gradient.

The head of liquid over the weir, based on a straight segmental downcomer, can be estimated by the following modification of the Francis weir formula:

$$h_o = \left(\frac{1.7Q_L}{l_w\sqrt{g}}\right)^{2/3} \tag{7}$$

where Q_L = volumetric flow rate of liquid, cfs, and l_w = weir length, ft.

Various investigators have proposed corrections for Eq. (7) to account for the curved sides of the tower and the approach velocity.[*] [†] In general, however, Eq. (7) gives adequate accuracy for design estimates of h_o.

The liquid gradient across the tray (h_g) can be approximated by use of the following equation developed by Davies: [‡]

For caps arranged on equilateral-triangle centers and caps covered with liquid to a depth not greater than 1 in.,

$$(h_gF_C)^{1.5}(1.5r - 1.4) + (h_gF_C)^{0.5}(3r)\left[h_w + h_o + \frac{s(l_r - l_c)}{l_c}\right] = \frac{0.42Q_Lr^{1.5}}{C_Dl_c} \tag{8}$$

where F_C = a correction factor to account for variations in gas rate and gas density; values of F_C are given in Fig. 16-8 as a function of $V\sqrt{\rho_G}$ and Q_L/W_T

r = number of rows of caps perpendicular to direction of liquid flow

s = skirt clearance, ft

l_r = total free space between risers perpendicular to direction of liquid flow, average of various rows, ft

l_c = total free space between caps perpendicular to direction of liquid flow, average of various rows, ft

C_D = liquid-gradient factor; value of C_D can be obtained from Fig. 16-8

V = superficial linear gas velocity (based on cross-sectional area of empty tower), fps

W_T = average width of tray normal to direction of liquid flow, ft, computed as average of total tray width at each row of caps

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[*] W. C. Edmister, *Petroleum Engr.*, no. 12, p. 193, 1948.

[†] J. H. Perry, "Chemical Engineers' Handbook," 3d ed., p. 409, McGraw-Hill Book Company, Inc., New York, 1950.

[‡] J. A. Davies, *Petroleum Refiner*, **29**(9):121 (1950); *Ind. Eng. Chem.*, **39**:774 (1947).

For caps arranged on square centers and for tunnel caps, replace the constants 0.42 and 1.4 in Eq. (8) by 0.37 and 1.0, respectively.

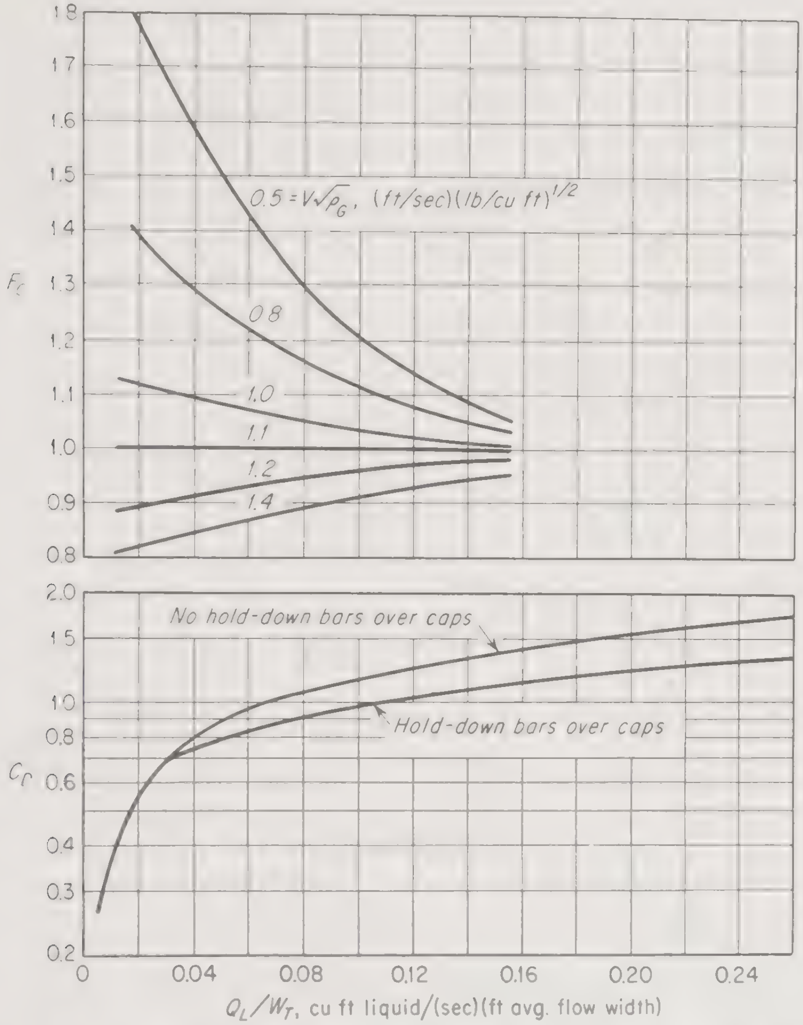

FIG. 16-8. Plot for evaluation of liquid-gradient factor C_D and correction factor F_c in Eq. (8).

All the variables in Eq. (8) except the liquid gradient are fixed by the tray design and the operating conditions, and the value of h_g can be determined by a trial-and-error or graphical procedure. Equation (8) is based on the assumption that the liquid level is below the top of the caps. In most bubble-cap towers, however, the liquid level is above the caps. Equation (8), therefore, is conservative for design estimates, since it tends to give high values for h_g.

Evaluation of Total Pressure Drop per Tray. The total pressure drop of the gas across a bubble-cap tray equals the sum of the pressure drop through the cap assembly and the pressure drop due to liquid head above the slots, or

$$h_T = h_c + h_{\text{slot}} + S_m + h_o + 0.5h_g \tag{9}$$

where h_T = head of liquid equivalent to total pressure drop of gas across tray, ft.

The total head h_T can be converted to conventional pressure units by the following equation:

$$\Delta p_T = \frac{h_T \rho_L}{144} \frac{g}{g_c} \tag{10}$$

where Δp_T = total pressure drop of gas across tray, psi, and g_c = conversion factor in Newton's law of motion, 32.17 ft-lb mass (sec)(sec)(lb force). In most cases, g and g_c are considered to be numerically equal.

Because the liquid on a bubble-cap tray is usually aerated, the clear-liquid density is greater than the density of the aerated liquid on the tray. Therefore, if ρ_L is taken as the clear-liquid density, the values of h_T and Δp_T given by Eqs. (9) and (10) may be high, and these values are often multiplied by 0.7 to give an approximate correction for the liquid aeration.

For a typical bubble-cap column, the following pressure drops per tray are considered reasonable:

Total pressure	*Pressure drop per tray*
30 mm Hg	3 mm Hg or less
1 atm	0.07–0.12 psi
300 psi	0.15 psi

Liquid Head in Downcomer. If the head of liquid in the downcomer is greater than the tray spacing plus the weir height, flooding will occur and liquid will build up on the trays. In design practice, the height of liquid in the downcomer (based on clear-liquid density) should be less than 50 per cent of the tray spacing.

Liquid head in the downcomer is composed of five individual heads as follows:

1. Weir height h_w, which is established by the tray design.
2. Height of crest over weir h_{ow}, which can be calculated by Eq. (7).
3. Liquid gradient h_g, which can be calculated by Eq. (8).
4. Head of liquid equivalent to the frictional flow resistance in the downcomer and in the passage of the fluid from the downcomer onto the plate. This head is usually relatively small, but it can be estimated as three kinetic heads for the liquid, based on the linear liquid velocity at the

minimum cross-sectional area for downcoming liquid flow,* or

$$h_d = \frac{3}{2g}\left(\frac{Q_L}{A_d}\right)^2 \tag{11}$$

where h_d = head of liquid equivalent to liquid pressure drop due to flow through downcomer and constriction, ft, and A_d = minimum cross-sectional area for downcoming liquid flow, sq ft.

5. Head of liquid which the gas must overcome as the gas passes through the next tray above. Assuming the same gas pressure drop over adjacent trays, this liquid head is equal to h_T.

The total head in the downcomer, H, as shown in Fig. 16-7, is equal to the sum of the preceding five heads, or

$$H = h_w + h_o + h_g + h_d + h_T \tag{12}$$

Combination of Eqs. (12) and (9) gives

$$H = 2h_o + 1.5h_g + h_w + h_d + h_c + h_{\text{slot}} + S_m \tag{13}$$

Example 2. Determination of Pressure Drop and Liquid Height in Downcomer for Bubble-cap Plate. The following specifications apply to a bubble-cap plate:

Diameter = 10.0 ft
Tray spacing = 26 in.
Liquid crossflow
Weir length = 6.2 ft
Weir height = 3.0 in.
Skirt clearance = 0.5 in.
Static submergence = 0.5 in.
Rectangular slots
Height of slots = 1.5 in.
Width of slots = 0.3 in.
Total riser cross-sectional area = 9 sq ft
Caps are bolted to tray (no hold-down bars)
Clearance between bottom of downcomer and plate = 2.5 in.
Number of rows of caps perpendicular to direction of liquid flow = 11
For an average row of caps perpendicular to direction of liquid flow, total free space between risers = 4.4 ft, total free space between caps = 2.7 ft, width of tray = 9 ft
Cross-sectional areas for vapor flow through riser, direction-reversal space, annular cap space, and slots are equal
Caps are arranged on equilateral-triangle centers staggered perpendicular to direction of liquid flow, and liquid depth above caps is less than 1 in.

This bubble-cap plate is to be used under the following conditions:

Vapor density = 0.15 lb/cu ft
Liquid density = 50 lb/cu ft
Superficial vapor velocity based on cross-sectional area of empty tower = 1.8 fps
Liquid flow rate = 1 cfs
Surface tension of liquid is such that Eq. (5) is applicable

Estimate the gas pressure drop across the tray and the liquid head in the downcomer.

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* J. J. Cicalese et al., *Proc. Am. Petroleum Inst.*, **26**(sec. III):180 (1946).

Solution

Liquid head equivalent to pressure drop through riser and cap (h_c):
By Eq. (4),

$$h_c = \frac{3V_c^2}{g} \frac{\rho G}{\rho L}$$

$$\text{Cross-sectional area of empty tower} = (10)^2 \frac{\pi}{4} = 78.5 \text{ sq ft}$$

V_c = linear velocity of gas in riser, reversal area, annular cap space, and slots

$$= \frac{(1.8)(78.5)}{9} = 15.7 \text{ fps}$$

$$h_c = \frac{(3)(15.7)^2(0.15)}{(32.17)(50)} = 0.069 \text{ ft}$$

Liquid head equivalent to pressure drop through slots (h_{slot}):
By Eq. (5),

$$h_{\text{slot}} = 1.5 \left(\frac{Q_s}{b}\right)^{2/3} \left[\frac{\rho G}{(\rho L - \rho G)g}\right]^{1/3}$$

Q_s = volumetric flow rate of gas per slot

$$= \frac{(15.7)(1.5)(0.3)}{144} = 0.049 \text{ cfs}$$

$$b = \text{slot width} = \frac{0.3}{12} \text{ ft}$$

$$h_{\text{slot}} = 1.5 \left(\frac{0.049}{0.3/12}\right)^{2/3} \left[\frac{0.15}{(50 - 0.15)(32.17)}\right]^{1/3} = 0.107 \text{ ft}$$

Height of liquid crest over weir (h_o):
By Eq. (7),

$$h_o = \left(\frac{1.7Q_L}{l_w \sqrt{g}}\right)^{2/3}$$

$$Q_L = \text{liquid flow rate} = 1.0 \text{ cfs}$$

$$l_w = \text{weir length} = 6.2 \text{ ft}$$

$$h_o = \left[\frac{(1.7)(1.0)}{(6.2)(32.17)^{1/2}}\right]^{2/3} = 0.132 \text{ ft}$$

Liquid gradient (h_g):
By Eq. (8),

$$(h_g F_C)^{1.5}(1.5r - 1.4) + (h_g F_C)^{0.5}(3r) \left[h_w + h_o + \frac{s(l_r - l_c)}{l_c}\right] = \frac{0.42 Q_L r^{1.5}}{C_D l_c}$$

r = rows of caps perpendicular to direction of fluid flow = 11
h_w = weir height = 3.0/12 = 0.25 ft
h_o = 0.132 ft
s = skirt clearance = 0.5/12 = 0.0416 ft
l_r = average total free space between risers perpendicular to direction of liquid flow = 4.4 ft
l_c = average total free space between bubble caps perpendicular to direction of liquid flow = 2.7 ft

V = superficial linear gas velocity based on empty tower = 1.8 fps
W_T = average tray width perpendicular to direction of fluid flow = 9 ft
$Q_L/W_T = \frac{1}{9} = 0.111$ cu ft/(sec)(ft)
$V\sqrt{\rho_G} = (1.8)(0.15)^{1/2} = 0.7$ (fps)(lb/cu ft)$^{1/2}$

From Fig. 16-8,

$$F_C = 1.12$$

$$C_D = 1.2$$

$$(h_g)^{1.5}(1.12)^{1.5}[(1.5)(11) - 1.4] + (h_g)^{0.5}(1.12)^{0.5}(3)(11)\left[0.25 + 0.132 + \frac{(0.0416)(4.4 - 2.7)}{2.7}\right] = \frac{(0.42)(1.0)(11)^{1.5}}{(1.2)(2.7)}$$

By trial and error,

$$h_g = 0.088 \text{ ft}$$

Pressure drop across tray based on clear-liquid density (Δp_T):
By Eq. (9), liquid head equivalent to the pressure drop across the tray is

$$h_T = h_c + h_{\text{slot}} + S_m + h_o + 0.5h_g$$

$$S_m = \text{static submergence} = \frac{0.5}{12} = 0.0416 \text{ ft}$$

$$h_T = 0.069 + 0.107 + 0.0416 + 0.132 + (0.5)(0.088) = 0.3936 \text{ ft}$$

By Eq. (10),

$$\Delta p_T = \frac{h_T \rho_L}{144}\frac{g}{g_c} = \frac{(0.3936)(50)(32.17)}{(144)(32.17)} = 0.137 \text{ psi}$$

Liquid head in downcomer (H):
By Eq. (12),

$$H = h_w + h_o + h_g + h_d + h_T$$

By Eq. (11), head due to liquid flow through downcomer constriction of area A_d is

$$h_d = \frac{3}{2g}\left(\frac{Q_L}{A_d}\right)^2$$

$$A_d = \text{(weir length)(clearance between downcomer and plate)}$$
$$= (6.2)\left(\frac{2.5}{12}\right) = 1.29 \text{ sq ft}$$

$$h_d = \frac{(3)}{(2)(32.17)}\left(\frac{1.0}{1.29}\right)^2 = 0.028 \text{ ft}$$

$$H = 0.25 + 0.132 + 0.088 + 0.028 + 0.3936 = 0.8916 \text{ ft}$$

Liquid head in downcomer based on clear-liquid density = (0.8916)(12) = 10.7 in.

Allowable Vapor Velocity. The vapor velocity in a bubble-cap column can be limited by the liquid-handling capacity of the downcomers or by entrainment in the rising gases. The ability of the downcomers to handle the liquid flow can be determined by the methods given in the preceding sections. In most cases, however, downcomer limitations do not set the allowable vapor velocity; instead, the common design basis for choosing allowable vapor velocities is a function of the amount of gas entrainment.

A tower must have sufficient cross-sectional area to handle the rising gases without excessive carry-over of liquid from one tray to another. By assuming that the frictional drag of the vapor on suspended liquid droplets should not exceed the average weight of a droplet, Souders and Brown * derived the following equation:

$$V_m = K_v \sqrt{\frac{\rho_L - \rho_G}{\rho_G}} \qquad (14)\,\dagger$$

where V_m = maximum allowable superficial vapor velocity (based on cross-sectional area of empty tower), fps, and K_v = an empirical constant, fps. An alternative form of Eq. (14) in terms of mass velocity follows:

$$G_m = V_m\rho_G = K_v\sqrt{\rho_G(\rho_L - \rho_G)} \qquad (15)$$

where G_m = maximum allowable mass velocity of vapor, lb (sec)(sq ft).

Equation (14) or (15) can be used as an empirical guide for estimating the maximum vapor velocities in plate columns. The constant K_v varies with plate spacing and depth of liquid above the bubble-cap slots. For design purposes, operating pressure and physical properties of the fluids are assumed to have no effect on K_v, although best results are obtained if the constant is based on data obtained with fluids and operating pressures similar to those involved in the particular design.

Carey ‡ has presented approximate values of K_v for generally acceptable commercial conditions. These values are shown in Fig. 16-9 as a function of tray spacing and *slot liquid seal*, where slot liquid seal is defined as the average depth of clear liquid above the top of the bubble-cap slots.

Although the allowable velocity given by Eq. (14) is conservative for many types of operations, such as commercial rectification of petroleum, many engineers employ vapor velocities in the range of 65 to 80 per cent of V_m to make certain their column will be operable. The allowable velocity is used to set the diameter of the column. The additional dimensions of the trays are then established, and an investigation of other limiting factors, such as downcomer capacity, should be made. Because Eq. (14) gives conservative results, the allowable vapor velocity obtained by use of the equation is usually applied to the total cross-sectional area of the

[*] M. Souders and G. G. Brown, *Ind. Eng. Chem.*, **26**:98 (1934).

[†] As a general rule of thumb, V_m should be near 3 fps for bubble-cap distillation towers operating at atmospheric pressure.

[‡] J. S. Carey, in J. H. Perry's "Chemical Engineers' Handbook," 3d ed., p. 598, McGraw-Hill Book Company, Inc., New York, 1950.

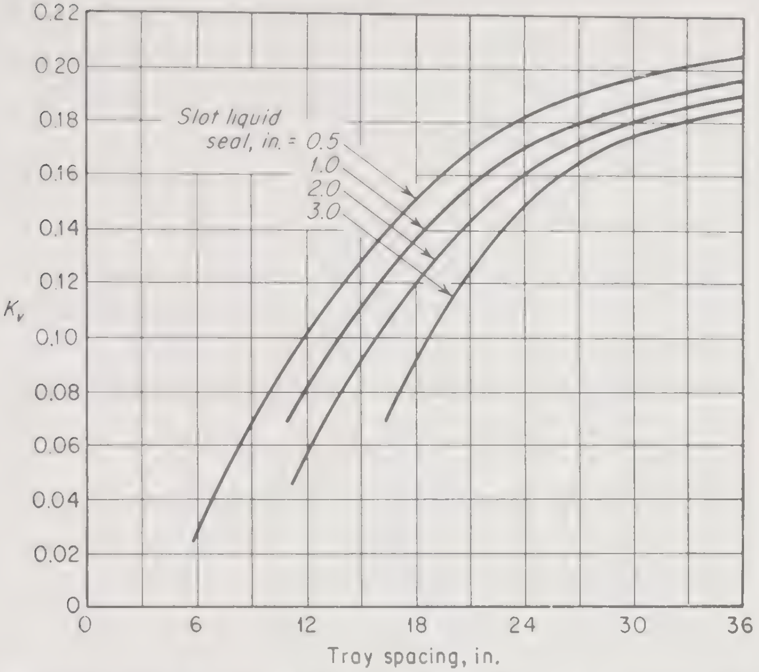

FIG. 16-9. Approximate values of constant K_v in Eq. (11) for maximum allowable vapor velocities in bubble-cap towers.

empty tower, with no allowance for the area occupied by ordinary types of downcomers.

In many cases, the vapor rate changes over the length of the tower, and the theoretical diameter based on the allowable velocity varies. Occasionally, two different diameters are used for different sections of one tower. Cost considerations, however, usually make it impractical to vary the diameter, and the constant diameter should be based on the tower location where allowable velocity and throughput rates require the largest diameter.

Example 3. Determination of Bubble-cap Column Diameter on Basis of Allowable Vapor Velocity. A bubble-cap distillation tower is to be operated under the following conditions:

	At top of tower	At bottom of tower
Vapor rate	270 lb mole/hr	300 lb mole/hr
Vapor molecular weight	70	110
Temperature	220°F	260°F
Pressure	1.0 atm	1.1 atm
Liquid density	44 lb/cu ft	42 lb/cu ft

The tray spacing is 24 in., and the average slot liquid seal is 2 in. The perfect-gas law can be assumed as applicable to the vapors. If the tower diameter is to remain constant over the entire length, estimate the minimum diameter.

Solution

From Fig. 16-9, $K_v = 0.16$

At top of tower,

$$\rho_G = \frac{(70)(492)}{(359)(680)} = 0.141 \text{ lb/cu ft}$$

$$\rho_L = 44 \text{ lb/cu ft}$$

$$V_m = 0.16\sqrt{\frac{44 - 0.141}{0.141}} = 2.82 \text{ fps}$$

$$\text{Minimum diameter} = \left[\frac{(70)(270)(4)}{(0.141)(\pi)(2.82)(3600)}\right]^{1/2} = 4.1 \text{ ft}$$

At bottom of tower,

$$\rho_G = \frac{(110)(492)(1.1)}{(359)(720)(1.0)} = 0.23 \text{ lb/cu ft}$$

$$\rho_L = 42 \text{ lb/cu ft}$$

$$V_m = 0.16\sqrt{\frac{42 - 0.23}{0.23}} = 2.16 \text{ fps}$$

$$\text{Minimum diameter} = \left[\frac{(110)(300)(4)}{(0.23)(\pi)(2.16)(3600)}\right]^{1/2} = 4.9 \text{ ft}$$

The limiting diameter occurs at the bottom of the tower; therefore, the minimum diameter based on the maximum allowable vapor velocity = 4.9 ft.

Plate Efficiencies

As discussed in the first part of this chapter, the design of mass-transfer equipment often requires evaluation of the number of theoretical stages necessary to accomplish a desired separation. To complete the design, information must be available that shows the relationship between these ideal values and the actual performance of the equipment. The translation of ideal stages into actual finite stages can be accomplished by the use of plate efficiencies.

Types of Plate Efficiency. Three kinds of plate efficiencies may be used for expressing the relationship between the performance of theoretical and actual stages. They are (1) over-all column efficiency or over-all plate efficiency, (2) Murphree plate efficiency, and (3) point efficiency or local efficiency.

The *over-all column efficiency* applies to the total number of stages and is defined as the number of theoretical stages required to produce a given separation divided by the number of stages actually necessary to produce the same separation. The *Murphree plate efficiency* applies to a single plate. It is defined as the ratio of the actual change in average vapor composition accomplished by a given plate to the change in average vapor composition if the vapors leaving the plate were in equilibrium with the liquid leaving the plate. The *point efficiency* is similar to the Murphree plate efficiency, except that the point efficiency applies to a single location on a given tray.

Although the over-all column efficiency has no fundamental mass-transfer basis, it is widely used because of its simplicity. The number of actual stages required for a given separation is simply equal to the number of theoretical stages divided by the over-all column efficiency. The Murphree plate efficiency is more fundamental than the over-all value, but it is less convenient to use because it must be applied to each individual plate. The point efficiency is of considerable theoretical interest but is seldom used in design practice because it requires knowledge of the variations in liquid composition across the tray and integration of the point efficiencies over the entire tray. Point efficiencies are always less than 100 per cent, but Murphree plate efficiencies may be greater than 100 per cent and are usually greater than point efficiencies on the same tray because of variation in liquid composition across the tray.

Factors Influencing Plate Efficiencies. The major factors that influence plate efficiencies are presented and discussed in the following:

Vapor Velocity. Peavy and Baker * have shown that plate efficiencies increase with increase in superficial vapor velocity (based on cross-sectional area of the empty tower) when the velocity is low, reach a fairly constant value over the range of velocities corresponding to normal acceptable operation, and then decrease at higher velocities. Slot velocities appear to have no appreciable effect on efficiency if they are kept in the range indicated by Eqs. (1) and (2).

Liquid Depth above Slots. Increase in depth of the liquid above the slots tends to increase the efficiency, especially if this liquid depth is less than 1 in.

Plate Spacing. Because of entrainment carry-over, the effect of plate spacing is related to the superficial vapor velocity. Too small a plate spacing can cause a low efficiency if the vapor velocity is greater than the allowable value.

Length of Liquid Path. The length of the liquid path across a tray is an important factor in determining the degree of liquid concentration gradient across the tray. Thus, if the length of the liquid path is long enough that an appreciable liquid concentration gradient is established, the Murphree plate efficiency is greater than the point efficiency. In general, as the length of the liquid path is increased, the over-all column efficiency increases.* The effect of liquid-path length is usually negligible if the length is less than 5 ft, but increasing the length to 10 to 15 ft may increase the over-all column efficiency by 20 to 40 per cent.

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* C. C. Peavy and E. M. Baker, *Ind. Eng. Chem.*, **29**:1056 (1937).

Liquid Resistance to Interphase Mass Transfer. Liquid viscosity, gas solubility in absorbers, and relative volatility in rectification columns are important factors in determining the liquid resistance to interphase mass transfer. Increase in liquid viscosity, decrease in gas solubility for absorbers, and increase in relative volatility for rectification columns cause an increase in the liquid resistance to interphase mass transfer and a resultant reduction in plate efficiency. The ratio of the liquid rate to the gas rate influences the relative importance of the liquid resistance to interphase mass transfer. An increase in the ratio of liquid rate to gas rate reduces the importance of the liquid resistance and can cause an increase in the plate efficiency.†

Other Factors. Design details of the column, such as slot dimensions, plate layout, or the total number of trays can have an effect on the efficiencies. The exact influence of these factors is best determined by empirical tests.

In multicomponent mass-transfer operations, the assumption is usually made that the same plate efficiency applies to all components. The over-all column efficiency is then considered in terms of the key components, and the same efficiency is assumed for the lighter and heavier components. This assumption is not necessarily correct because of the different properties of the components. More exact results can be obtained by using Murphree plate efficiencies and accounting for the difference in efficiencies.

Correlations for Estimation of Plate Efficiencies. Over-all column efficiencies are based on performance data, and no exact correlation of the results obtained with various mixtures and types of columns can be presented. Many generalized correlations have been developed, however, and these are useful for making design estimates when no other data are available.

For standard types of bubble-cap columns operated in the range of allowable velocities where the over-all column efficiencies are essentially constant, O'Connell has correlated efficiency data on the basis of liquid viscosity and relative volatility (or gas solubility).‡ The results for fractionators and absorbers are presented in Fig. 16-10. This correlation is based, primarily, on experimental data obtained with bubble-cap columns having a liquid path of less than 5 ft and operated at a reflux ratio near the minimum value. Figure 16-10 is adequate for design estimates with most types of commercial equipment and mixtures, although efficiencies

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* M. G. Gautreaux and H. E. O'Connell, *Chem. Eng. Progr.*, **51**:233 (1955).

† G. C. Williams, E. K. Stigger, and J. H. Nichols, *Chem. Eng. Progr.*, **46**:7 (1950).

‡ H. E. O'Connell, *Trans. AIChE*, **42**:751 (1946).

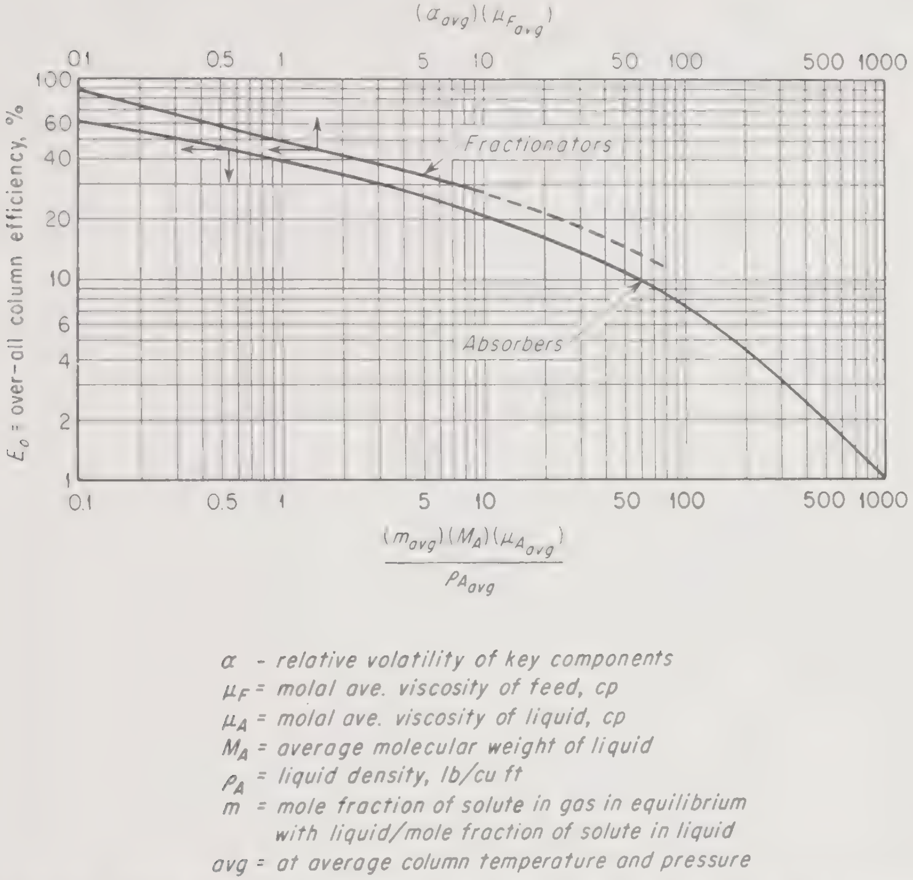

FIG. 16-10. Over-all column efficiencies for bubble-cap tray fractionators and absorbers.

determined directly from equipment operating near the conditions involved in the design are always to be preferred.*

Chu has extended the correlation shown by Fig. 16-10 to include the effects of liquid submergence and the ratio of liquid flow rate to vapor flow rate. He presents the following simplified equations for estimating over-all column efficiencies: †

For fractionators,

$$\log E_o = 1.67 - 0.25 \log (\mu_{F,\text{avg}}\alpha_{\text{avg}}) + 0.30 \log \frac{L'_M}{V'_M} + 0.09\left(S_m + \frac{c}{2}\right) \quad (16)$$

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* Data on over-all column efficiencies and Murphree plate efficiencies for fractionators and absorbers, with information on equipment construction, fluids, and operating conditions, are given in J. H. Perry, "Chemical Engineers' Handbook," 3d ed., pp. 616, 699, McGraw-Hill Book Company, Inc., New York, 1950.

† J. C. Chu et al., *J. Appl. Chem.*, **1**:529 (1951).

For absorbers,

$$\log E_o = 1.60 - 0.38 \log \frac{m_{\text{avg}} M_A \mu_{A,\text{avg}}}{\rho_{A,\text{avg}}} + 0.25 \log \frac{L'_M}{V'_M} + 0.09\left(S_m + \frac{c}{2}\right) \quad (17)$$

where E_o = over-all column efficiency, per cent
S_m = static submergence, ft
c = slot height, ft
L'_M = molal liquid flow rate, lb mole/hr
V'_M = molal vapor flow rate, lb mole/hr
$\mu_{F,\text{avg}}$, α_{avg}, m_{avg}, M_A, $\mu_{A,\text{avg}}$, $\rho_{A,\text{avg}}$ are as defined in Fig. 16-10

Equations (16) and (17) are based on the relationships shown by Fig. 16-10 plus additional experimental results on the effects of liquid submergence and the ratio L'_M/V'_M. Use of these equations should be limited to conditions in which the ratio L'_M/V'_M is in the range of 0.4 to 8 and the static submergence plus one-half the slot height is less than 1.5 in.

A simplified empirical equation for bubble-cap columns operating on petroleum and similar hydrocarbons has been presented by Drickamer and Bradford.* Their results are based on plant tests with 54 refinery columns used for distillation or absorption of hydrocarbons. The columns were of the standard bubble-cap or perforated-plate type operated under typical refinery conditions. The results were correlated on the basis of the single variable, liquid viscosity, to give

$$E_o = 17 - 61.1 \log \mu_{F,\text{avg}} \quad (18)$$

Use of Eq. (18) should be limited to commercial towers for which no other data are available. It gives adequate results for the fractionation of petroleum and similar hydrocarbons, but it is not recommended if the relative volatility of the key components is greater than 4.0 or if the value of $\mu_{F,\text{avg}}$ is outside the range of 0.07 to 1.4 centipoises.

Example 4. Estimation of Over-all Column Efficiency. A continuous fractionation unit has been designed to operate on a liquid feed containing components A, B, C, and D. Calculations have shown that 20 theoretical stages are necessary in the column, not including the reboiler. On the basis of the following data, estimate the over-all column efficiency and the number of actual trays needed in the column by (*a*) Fig. 16-10, (*b*) Eq. (16), and (*c*) Eq. (18):

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* H. G. Drickamer and J. R. Bradford, *Trans. AIChE*, **39**:319 (1943); *Petroleum Refiner*, **22**(10):105 (1943).

Component	Mole fraction in			Viscosity of liquid at 260°F, centipoises
	Feed	Overhead	Bottoms	
A	0.10	0.25	....	0.040
B	0.30	0.70	0.03	0.110
C	0.40	0.05	0.64	0.138
D	0.20	....	0.33	0.175

Materials *B* and *C* are considered as the key components.

Relative volatility of the key components is independent of concentration and equals 1.94 at 260°F and the average column pressure. Feed temperature = 85°F. Overhead temperature = 240°F. Bottoms temperature = 280°F.

The fractionating unit is a bubble-cap tray column with a standard type of tray design. The vapor velocity through the tower is about 90 per cent of the maximum allowable value.

Tower diameter = 4.8 ft. Height of bubble-cap slots = 1.5 in. Static submergence = 0.5 in. The ratio L'_M/V'_M is 0.7 in the rectifying section of the column and 1.2 in the stripping section.

Solution

Average column temperature = (280 + 240)/2 = 260°F.

Molal average viscosity of feed at average column temperature = $\mu_{F,\text{avg}} = (0.040)(0.10) + (0.110)(0.30) + (0.138)(0.40) + (0.175)(0.20) = 0.127$ centipoise.

At the average column temperature, relative volatility based on overhead concentration equals the relative volatility based on the bottoms concentration; therefore, average relative volatility of key components at average column temperature = $\alpha_{\text{avg}} = 1.94$.

Since L'_M/V'_M is different in the rectifying and stripping sections, an average value must be used, or else a separate efficiency for each section can be obtained. In this case an arithmetic-average value is adequate:

$$\frac{L'_M}{V'_M} = \frac{0.7 + 1.2}{2} = 0.95$$

Height of bubble-cap slots = $c = 1.5/12 = 0.125$ ft. $c/2 = 0.0625$ ft.

Static submergence = $S_m = 0.5/12 = 0.0416$ ft.

(*a*) Efficiency and total number of trays by Fig. 16-10:

$$(\alpha_{\text{avg}})(\mu_{F,\text{avg}}) = (1.94)(0.127) = 0.246$$

From Fig. 16-10,

$$E_o = 70\%$$

$$\text{Number of actual trays needed in column} = \frac{20}{0.7} = 29$$

(*b*) Efficiency and total number of trays by Eq. (16):

$$\log E_o = 1.67 - 0.25 \log 0.246 + 0.3 \log 0.95 + 0.09(0.0416 + 0.0625)$$

$$E_o = 66\%$$

$$\text{Number of actual trays needed in column} = \frac{20}{0.66} = 31$$

(*c*) Efficiency and total number of trays by Eq. (18):

$$E_o = 17 - 61.1 \log 0.127 = 72\%$$

$$\text{Number of actual trays needed in column} = \frac{20}{0.72} = 28$$

Modified Bubble-cap Towers

Uniflux Trays. Many modifications of conventional bubble-cap towers have been developed in an effort to reduce costs, reduce pressure drop, equalize vapor flow through the caps, increase plate efficiencies, or, in general, improve the operating performance of the tower. Socony-Vacuum's Uniflux tray is a typical example.* The Uniflux tray consists of a series of interlocking S-shaped sections which are assembled in the form of tunnel caps with slot outlets on one side only. Segmental downcomers, similar to the downcomers in conventional bubble-cap columns, are provided.

The vapors issue from the Uniflux caps in only one direction, and in such a manner as to reduce the liquid gradient across the tray. This tends to equalize the slot submergence and give equal vapor distribution among the caps. The total slot area per tray is usually in the range of 12 to 14 per cent of the total cross-sectional area of the tower, and the riser area may be two to four times greater than that used in conventional bubble-cap towers.

The simplified construction of the Uniflux tray results in costs that are 30 to 50 per cent cheaper than costs for equivalent bubble-cap trays of conventional design. The combination of equal slot submergence, low entrainment due to directing the vapors horizontally into the liquid, and low pressure drop in the risers and vapor-reversal sections gives the Uniflux tray large capacities and high plate efficiencies.

Flexitrays and Float-valve Trays. Equalized distribution of vapors through the bubble caps can be achieved by throttling the flow through the caps. In the Flexitray,† a liftable disk-type valve is provided with each cap. As the vapor rate increases, the valve is lifted to give a larger opening until, at about 60 per cent of capacity, the disk-type valve is completely open. The vapors are directed horizontally into the liquid in order to achieve high plate efficiencies. Because of the variation in available vapor-delivery area with vapor rate, the Flexitray shows good operating characteristics over a wide range of capacities. Float-valve trays* operate on the same principle as the Flexitray, except that a floating pivotal valve is used in each cap instead of a liftable disk-type valve.

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* V. O. Bowles, *Chem. Eng.*, **61**(5):174 (1954).

† G. C. Thrift, *Chem. Eng.*, **61**(5):177 (1954).

Sieve-tray (or Perforated-plate) Towers†‡

A sieve tray consists of a flat plate perforated with many small holes. Liquid flows across the plate and passes over a weir into a downcomer, as in a bubble-cap column. The upward flow of the vapor keeps the liquid from flowing through the holes, and the operation of the tray is basically the same as that of a bubble-cap tray. When the sieve tray is properly designed, it is stable over a wide range of flow rates. Comparison of sieve trays with conventional bubble-cap trays at equivalent operating conditions shows that the plate efficiencies are about the same, pressure drop with sieve trays is less, and sieve trays are cheaper.

Holes in the sieve trays may be drilled or punched, and hole sizes of $\frac{1}{8}$ or $\frac{3}{16}$ in. on $\frac{3}{8}$- or $\frac{9}{16}$-in. triangular pitch have been found to give satisfactory results. A total hole area in the range of 6 to 15 per cent of the tower cross-sectional area is conventional. The gas pressure drop across the tray equals the pressure drop due to passage of vapor through the holes plus the pressure drop due to the head of liquid on the tray.

Turbogrid Trays§

Turbogrid trays are similar to sieve trays, except that no downcomers are necessary and slots are used instead of circular holes. A typical Turbogrid tray consists of a flat grid of parallel slots. The liquid flows from tray to tray through the same slot openings used by the rising vapors. The slots can be stamped perforations in a flat metal sheet or the open spaces between parallel bars.

The simple design of Turbogrid trays causes them to be cheaper than conventional bubble-cap trays. Experimental tests have shown that, at equivalent operating conditions, Turbogrid trays have 20 to 100 per cent greater capacity than bubble-cap trays, approximately the same height per theoretical stage, and 40 to 80 per cent lower pressure drop. Because both the liquid and vapor pass through the slots, the operating range where stable conditions exist is smaller with Turbogrid trays than with bubble-cap or sieve trays.

* I. E. Nutter, *Chem. Eng.*, **61**(5):176 (1954).

† F. D. Mayfield et al., *Ind. Eng. Chem.*, **44**:2238 (1952).

‡ D. C. Lee, Jr., *Chem. Eng.*, **61**(5):179 (1954).

§ Shell Development Co. Eng. Staff, *Chem. Eng. Progr.*, **50**:57 (1954); *Petroleum Refiner*, **31**(11):105 (1952).

CONTINUOUS CONTACTORS—PACKED TOWERS

As illustrated in Fig. 16-11, the common type of packed tower consists of a cylindrical shell containing an inert packing material. These towers usually operate with countercurrent fluid flow. For the case in which liquid and vapor phases are involved, the liquid descends through the column in the form of films distributed over the packing surface, and the vapors rise through the spaces between the packing particles. Consequently, a large amount of vapor-liquid contact area becomes available, thus resulting in efficient mass-transfer operations.

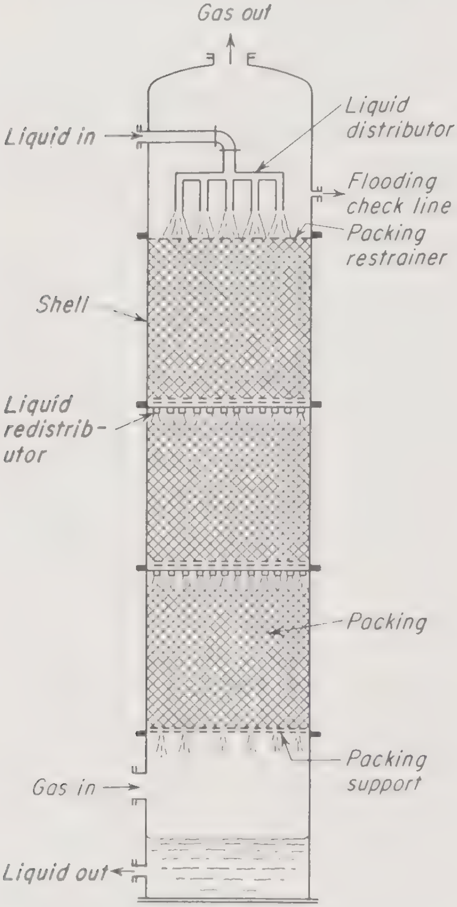


FIG. 16-11. Cross-sectional view of packed tower in operation.

The design of a packed tower requires consideration of mechanical factors, such as pressure drop, foundation load, and flow capacities. In addition, consideration must be given to the factors that influence the effectiveness of contact between the fluid phases. A satisfactory packing should have the following properties:

1. *Low pressure drop.* Since the pressure drop through the packing is a direct function of the fluid velocities, a large free cross-sectional area should be available between the packing particles in order to give a low pressure drop.

2. *High capacity.* The packing should permit high fluid rates without excessive pressure drop or build-up of liquid in the tower. Because flooding or carry-over of liquid out of the tower can occur above certain limiting fluid velocities, a large free cross-sectional area is desirable for high capacities.

3. *Low weight and low liquid holdup.* The total weight of the column and the resultant foundation load is low if the weight of the packing and the liquid holdup in the tower are low. The amount of liquid holdup, how-

ever, must be sufficiently great to retain an effective driving force for mass transfer.

4. *Large active surface area per unit volume.* To give high efficiencies, the packing must provide a large amount of contact area between the two fluid phases. This can be accomplished by using irregularly shaped packings that permit extensive distribution of liquid over surface area which can be contacted directly by the second fluid.

5. *Large free volume per unit total volume.* This property is particularly important if time must be available for a gas-phase chemical reaction, such as the oxidation of nitric oxide in the aqueous absorption of nitrogen dioxide.

6. *Miscellaneous.* High durability. High corrosion resistance. Low side thrust on tower walls. Low cost.

Types of Packing

Although many different types of packing are available for obtaining efficient contact between two fluid phases, the types can generally be classified as *random* or *stacked*. A random packing is one that is merely dumped into a containing shell, and the individual pieces are not arranged

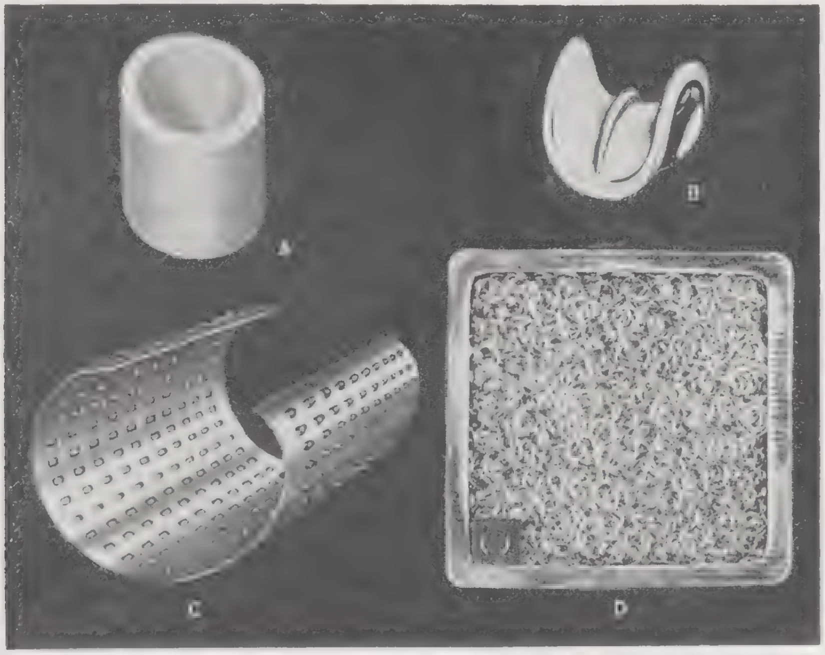


FIG. 16-12. Single pieces of typical random packings. (A) Raschig ring. (*Maurice A. Knight Company.*) (B) Berl saddle. (*Maurice A. Knight Company.*) (C) Cannon protruded packing. (*Scientific Development Company.*) (D) Fenske helices. (*Courtesy of M. R. Fenske.*)

in any particular pattern. Raschig rings and Berl saddles are the most common of the random packings used in industrial operations.

Raschig rings, as illustrated in Fig. 16-12, are simply hollow cylinders with the outside diameter equal to the height. They are usually made of inert materials that are cheap and light, such as porcelain, chemical stoneware, or carbon. Other materials of construction, such as clay, plastic, steel, and metal alloys, are also used. Raschig rings are available in sizes ranging from $^1/_4$ to 3 in. or more. Because breakage of fragile packing may occur when the pieces are dropped into an open shell, the initial packing charge is sometimes made by filling the empty tower with water and then dumping the packing slowly into the water.

Additional active surface area can be provided by adding a single web or a cross web on the inside of a Raschig ring. When a single web is present, the packing is known as *Lessing rings*, and, with a cross web, the packing is known as *cross-partition rings*. Cross-partition rings are available in sizes ranging from 3 to 6 in., and they are almost always used as a stacked packing.

Saddle-shaped packings, such as Berl saddles and Intalox saddles, are available in sizes from $^1/_4$ to 2 in. These packings are formed from chemical stoneware or from any other material that can be shaped by punch dies. They form an interlocking structure which gives less side thrust and more active surface area per unit volume than Raschig rings.

Many types of highly efficient packings have been developed for use in small-diameter columns. Two examples, Cannon protruded packing and Fenske helices, are shown in Fig. 16-12.

Stacked packings, in general, give lower pressure drops for equivalent fluid capacities than random packings. However, this advantage is gained at the expense of higher initial costs due to the extra installation labor. Raschig rings and Lessing rings of nominal sizes 3 in. or larger are often used as a stacked packing. Other examples of stacked packings are shown in Fig. 16-13. A list of the important physical characteristics for common packings used in industrial operations is presented in Table 3.

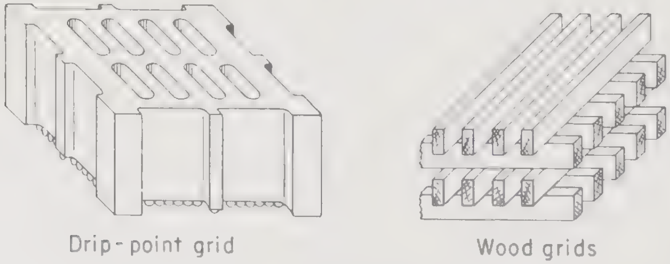


FIG. 16-13. Stacked grid packings.

TABLE 3. PHYSICAL CHARACTERISTICS OF COMMERCIAL TOWER PACKINGS

For use when direct experimental data are not available

Packing	Nominal size, in.	Approximate average weight per cu ft of tower volume, lb	Approximate average total surface area of packing, sq ft/cu ft of tower volume	Per cent free-gas space $= \epsilon \times 100$	Packing factor * $= a_p/\epsilon^3$, effective surface area/(void fraction)^3, sq ft per cu ft of tower volume (dry-packed values for use with Fig. 16-17)
Random packings:					
Stoneware Raschig rings †	¼	46	240	73	768
	⅜	51	134	68	494
	½	50	122	64	517
	¾	44	80	73	199
	1	40	58	73	150
	1½	42	35	68	108
	2	37	28	74	46
	3	40	19	74	
Carbon Raschig rings †	½	27	114	74	373
	1	27	57	74	170
	1½	34	38	67	92
	2	27	29	74	56
Steel Raschig rings † (wall thickness = 1⁄16 in.)	½	132	118	73	
	1	73	57	85	
	2	38	31	92	
Lessing rings † (porcelain)	1	50	69	66	
	½	58	40	60	
	2	49	32	68	
Intalox saddles † (porcelain)	½	34	190	78	
	1	34	78	78	100 ‡
	1½	30	60	81	52 ‡
Berl saddles § (porcelain)	¼	56	274	58	4225
	½	54	155	60	574
	1	45	79	69	229
	1½	38	52	70	79
Stacked packings (stacked for maximum surface area per unit of tower volume):					
Raschig rings ¶	2		32	80	

TABLE 3. PHYSICAL CHARACTERISTICS OF COMMERCIAL TOWER PACKINGS (*Continued*)

Packing	Nominal size, in.	Approximate average weight per cu ft of tower volume, lb	Approximate average total surface area of packing, sq ft/cu ft of tower volume	Per cent free-gas space $= \epsilon \times 100$	Packing factor * $= a_p/\epsilon^3$, effective surface area/(void fraction)^3, sq ft per cu ft of tower volume (dry-packed values for use with Fig. 16-17)
Single-spiral rings † (porcelain)	$4 \times 4 \times \frac{3}{8}$	61	32	60	
	$6 \times 6 \times \frac{1}{2}$	59	21	66	
Cross-partition rings † (porcelain)	$4 \times 4 \times \frac{3}{8}$	81	32	53	
	$6 \times 6 \times \frac{5}{8}$	70	21	48	
Drip-point grids ¶	No. 6146, General Ceramic Company	72	18	48	

* W. E. Lobo et al., *Trans. AIChE*, **41**:693 (1945).

† M. Leva, "Tower Packings and Packed Tower Design," 2d ed., pp. 7–14, U.S. Stoneware Company, Akron, Ohio, 1953.

‡ M. Leva, *Chem. Eng. Progr., Symposium Ser.*, **50**(10):51 (1954).

§ M. Leva et al., "Fluid Flow through Packed and Fluidized Systems," *U.S. Bureau of Mines Bull.* 504, 1951.

¶ M. Molstad et al., *Trans. AIChE*, **38**:405 (1942).

Liquid Distribution

In absorption and distillation towers, the packing should be wetted completely by the descending liquid in order to provide the maximum amount of active surface area. For this reason, the entering liquid should be distributed uniformly over the top of the packing at a flow rate sufficient to permit wetting of all the packing surface. The packing support plate should provide ample space for passage of both liquid and gas with good distribution of the gas. A cone-shaped packing support is often used in small columns to distribute the entering gas uniformly throughout the packing and reduce the possibility of liquid flooding at the support plate.

Even with distributors at the top and bottom of the tower, the descending liquid has a tendency to channel or flow toward the column wall, thus resulting in packing regions where the surface is dry. Stacked packings do not give so good liquid distribution as random packings, and, in general, distribution difficulties tend to become excessive if the ratio of tower diameter to packing diameter is less than 7.

Loss of active surface area due to improper liquid distribution can be reduced by using intermediate redistributor plates, as shown in Fig. 16-11. Complete wetting of the packing by preflooding the column at the start of the operation or use of a self-wetting packing, such as protruded packing, can decrease the detrimental effects of poor liquid distribution.

Pressure Drop

The primary factors that affect pressure drop in packed towers are (1) fluid-flow rates, (2) density and viscosity of the fluids, and (3) size, shape, orientation, and surface of the packing particles. Figure 16-14 illustrates the effects of fluid rates at constant operating pressure, and Fig. 16-16 shows how increased gas velocity due to reduction in operating pressure can affect the pressure drop.

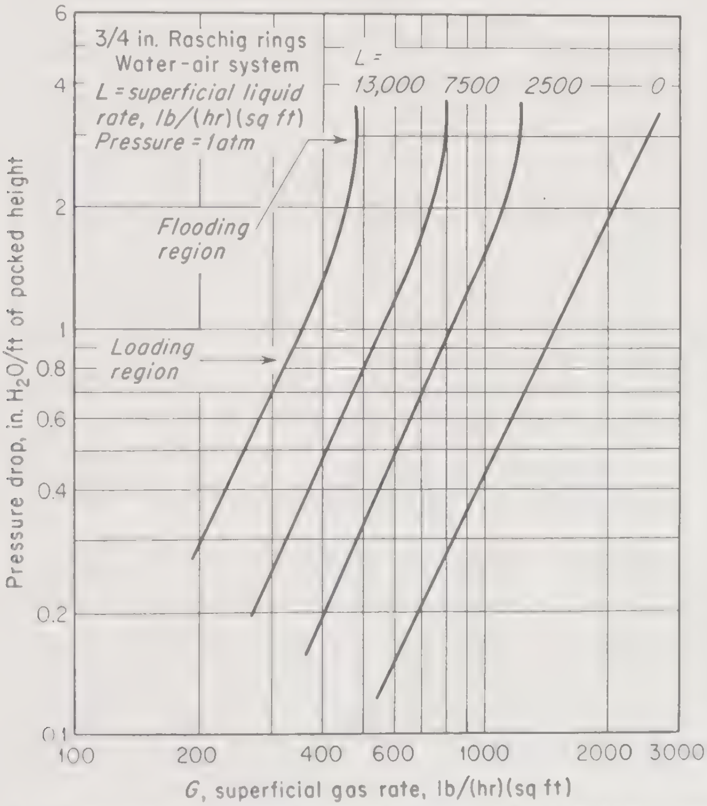


FIG. 16-14. Packed-tower pressure drop as function of gas rate and liquid rate.

As indicated by Figs. 16-14 through 16-16, a log-log plot of pressure drop per foot of packed height versus gas rate gives a straight-line relationship over the lower range of pressure drops. The point where the line first starts to curve upward is often designated as the *loading point*, to indicate that liquid is starting to build up in the column and is reducing the effective free space for gas flow. At the *flooding point* the pressure-drop-versus-gas-rate curve becomes almost vertical, and a liquid layer starts to build up on top of the packing. The flooding point represents the upper limiting conditions of pressure drop and fluid rates for practical tower operation.

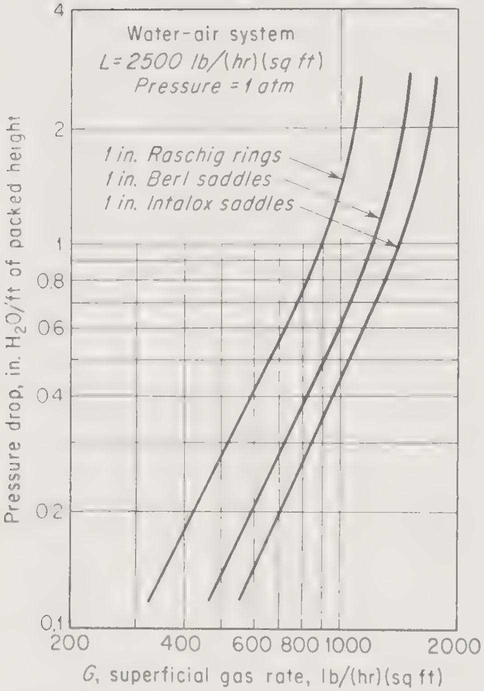
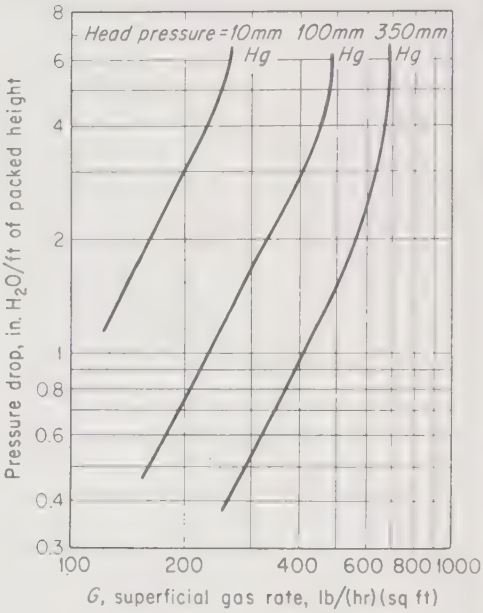


FIG. 16-15. Packed-tower pressure drop as function of gas rate and type of packing.



1/4 in. Berl saddles
n-decane — trans-decalin
Column diameter = 2 in.
Packed height = 2 ft
Total reflux (L = G)

FIG. 16-16. Pressure drop in packed distillation tower as function of gas rate and operating pressure.

Estimation of Pressure Drop in Packed Towers. Many methods have been proposed for estimating pressure drop in packed towers.[*] Most of these methods are based primarily on experimental data obtained with countercurrent flow of water and air through various types of packed towers. Because of the empirical nature of these correlations and the fact that the effects of some of the variables are not included, it is always best to predict pressure drops in the design of packed towers on the basis of experimental data obtained with equipment operating under conditions equivalent to those involved in the design.* If such data are not available, approximations can be made by using the methods outlined in the following discussion.

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[*] T. K. Sherwood and R. L. Pigford, "Absorption and Extraction," 2d ed., McGraw-Hill Book Company, Inc., New York, 1952.

S. Ergun, *Chem. Eng. Progr.*, **48**:89 (1952).

M. Leva, *Chem. Eng. Progr., Symposium Ser.*, **50**(10):51 (1954).

F. A. Zenz, *Chem. Eng. Progr.*, **43**:415 (1947); *Chem. Eng.*, **60**(8):176 (1953).

Irrigated Packings. Because the operation of packed towers in the range between the loading region and the flooding point may give erratic fluctuations, many packed towers are operated in the preloading range. In this range, the slope of the straight lines in Figs. 16-14 through 16-16 is approximately 2.0, and the pressure drop can therefore be taken as directly proportional to the square of the gas mass velocity.

TABLE 4. CONSTANTS FOR ESTIMATING PRESSURE DROP IN PACKED TOWERS BY EQ. (19)

Apply only to preloading range. Above this range, pressure drop predicted by Eq. (19) will be too low.

Packing	Nominal size, in.	$\gamma \times 10^8$	$\Phi \times 10^3$	Valid for range of L, lb/(hr)(sq ft)
Raschig rings	½	139	7.2	300–9000
	¾	33	4.5	2000–11,000
	1	32	4.3	400–27,000
	1½	12	4.0	700–18,000
	2	11	2.3	700–22,000
Berl saddles	½	60	3.4	300–14,000
	¾	24	3.0	400–14,000
	1	16	3.0	700–29,000
	1½	8	2.3	700–22,000
Intalox saddles	1	12	2.8	2500–14,000
	1½	6	2.3	2500–14,000
Drip-point grids (cross flue)	No. 6146, General Ceramic Company	1.2	2.3	300–18,000

Leva † has correlated experimental data to obtain the following empirical equation for estimating pressure drop in packed beds under preloading conditions with simultaneous counterflow of liquid and gas:

$$\frac{\Delta p}{h} = \gamma(10)^{\Phi L/\rho_L} \frac{G^2}{\rho_G} \qquad (19)$$

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* For a compilation of various experimental data, see J. H. Perry, "Chemical Engineers' Handbook," 3d ed., p. 680, McGraw-Hill Book Company, Inc., New York, 1950.

† M. Leva, *Chem. Eng. Progr., Symposium Ser.*, **50**(10):51 (1954).

where Δp = pressure drop, psf
h = packed height, ft
γ, Φ = constants with value dependent on packing size and type (see Table 4)
L = superficial liquid mass velocity (based on cross-sectional area of empty tower), lb/(hr)(sq ft)
ρ_L = density of liquid, lb/cu ft
G = superficial gas mass velocity (based on cross-sectional area of empty tower), lb/(hr)(sq ft)
ρ_G = density of gas, lb/cu ft

The effect of liquid viscosity is not included in Eq. (19). Although an increase in liquid viscosity tends to cause an increase in pressure drop if flow rates are held constant, the results of Eq. (19) can be accepted as a

Table 5. Pressure Drop at Flooding Point in Packed Towers

Values are based on countercurrent flow of liquid and air at atmospheric pressure.

In the range between the loading region and the flooding point, an approximation of the pressure drop Δp at a gas mass velocity G can be obtained from the following equation:

$$\Delta p = \Delta p_F \left(\frac{G}{G_m}\right)^{3.2}$$

The pressure drop at the loading point is usually in the range of one-fourth to one-sixth of the pressure drop at the flooding point.

Packing	Nominal size, in.	Pressure drop at flooding point, $\Delta p_F/h$, in. water/ft of packed height						
		Kinematic viscosity of liquid, centistokes = centipoises/specific gravity						
		0.6	1.0	3.0	6.0	10	20	40
Raschig rings...	¼	4.4	4.0	3.3	3.0	2.8	2.6	2.4
	½	3.9	3.5	2.9	2.7	2.5	2.3	2.1
	¾	3.3	3.0	2.5	2.3	2.1	1.9	1.8
	1	3.3	3.0	2.5	2.3	2.1	1.9	1.8
	1½	2.8	2.5	2.1	1.9	1.8	1.6	1.5
	2	2.8	2.5	2.1	1.9	1.8	1.6	1.5
Berl saddles....	¼	1.4	1.3	1.2	1.1	1.0	1.0	0.9
	½	2.1	2.0	1.8	1.7	1.6	1.5	1.4
	¾	2.7	2.5	2.3	2.1	2.0	1.9	1.8
	1	2.7	2.5	2.3	2.1	2.0	1.9	1.8
	1½	2.4	2.2	2.0	1.8	1.7	1.6	1.5

reasonable approximation if the liquid involved has a viscosity less than about 2 centipoises.

At the flooding point for a given packing and set of fluids, the pressure drop per foot of packed height remains approximately constant with variations in fluid rates and operating pressure. Table 5 presents typical pressure drops for various fluids and packings at the flooding point.* The table also indicates a method for estimating pressure drop when a packed column is operated in the range between the loading point and the flooding point.

Dry Packings. The following equation, proposed by Ergun,† can be used to estimate pressure drop caused by the flow of a gas through dry packings:

$$\frac{\Delta p}{h} = \frac{1-\epsilon}{\epsilon^3} \frac{G^2}{d_p g_c \rho_G} \left[\frac{150(1-\epsilon)\mu_G}{d_p G} + 1.75 \right] \tag{20}$$

where ϵ = fractional void volume in bed, cu ft void/cu ft of packed-tower volume
μ_G = absolute viscosity of gas, lb/(ft)(hr)
d_p = effective diameter of packing particle, ft, or diameter of a sphere with same surface-to-volume ratio as packing particle
= $6(1-\epsilon)/a_p$
a_p = surface area of packing per unit of packed-tower volume, sq ft/cu ft

Equation (20) accounts for simultaneous kinetic and viscous energy losses, and it is applicable to the single-phase flow of liquids as well as gases.

Example 5. Estimation of Pressure Drop in Packed Tower. A column 2 ft in diameter is packed with $\frac{3}{4}$-in. stoneware Raschig rings. Air, at an average pressure of 1 atm and an average temperature of 70°F, flows through the tower at a superficial mass velocity of 600 lb/(hr)(sq ft). Estimate the pressure drop through the dry packing by Eq. (20). If water at 70°F flows countercurrent to the air at a rate of 8000 lb/hr, estimate the pressure drop by Eq. (19). Express the answers as inches of water per foot of packed height, and compare the calculated results with the values shown in Fig. 16-14.

Solution

Dry packing: Eq. (20) applies.

$$\frac{\Delta p}{h} = \left(\frac{1-\epsilon}{\epsilon^3}\right) \frac{G^2}{d_p g_c \rho_G} \left[\frac{150(1-\epsilon)\mu_G}{d_p G} + 1.75 \right]$$

From Table 3,
$\epsilon = 0.73$
a_p (based on total surface area) = 80 sq ft/cu ft

$$d_p = \frac{6(1-\epsilon)}{a_p} = \frac{6(1-0.73)}{80} = 0.0202 \text{ ft}$$

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* F. A. Zenz, *Chem. Eng.*, **60**(8):176 (1953).

† S. Ergun, *Chem. Eng. Progr.*, **48**:89 (1952).

μ_G (at 70°F) = 0.018 centipoise = 0.018 × 2.42 = 0.044 lb/(ft)(hr)

$$\rho_G = \frac{(29)(492)}{(359)(530)} = 0.075 \text{ lb/cu ft}$$

$$\frac{\Delta p}{h} = \frac{1 - 0.73}{(0.73)^3} \frac{(600)^2}{(0.0202)(32.17)(3600)^2(0.075)} \left[\frac{150(1 - 0.73)(0.044)}{(0.0202)(600)} + 1.75 \right]$$

$$= 0.67 \text{ lb/(sq ft)(ft)} = \frac{(0.67)(33.93)(12)}{(14.7)(144)} = 0.13 \text{ in. water/ft}$$

According to Fig. 16-14, $\Delta p/h$ = about 0.15 in. water/ft.
Irrigated packing: Eq. (19) applies.

$$\frac{\Delta p}{h} = \gamma(10)^{\Phi L/\rho_L} \frac{G^2}{\rho_G}$$

From Table 4,
$\gamma = 33 \times 10^{-8}$
$\Phi = 4.5 \times 10^{-3}$
$\rho_L = 62.3$ lb/cu ft
$L = \dfrac{8000}{(\pi/4)(2)^2} = 2550$ lb/(hr)(sq ft)

$$\frac{\Delta p}{h} = 33 \times 10^{-8}(10)^{0.0045\times2550/62.3} \frac{(600)^2}{(0.075)} = 2.42 \text{ lb/(sq ft)(ft)}$$

$$= \frac{(2.42)(33.93)(12)}{(14.7)(144)} = 0.47 \text{ in. water/ft}$$

According to Fig. 16-14, $\Delta p/h$ = about 0.48 in. water/ft.

Allowable Vapor Velocity

The limiting vapor velocity for practical operation of a packed tower is set by the flooding point. As in the case of bubble-cap plate towers, the design engineer can determine the necessary diameter of a packed tower on the basis of the limiting vapor velocity. The maximum allowable vapor velocity is commonly designated as the superficial velocity at the flooding conditions. Because the tower operation may become unstable as the flooding point is approached, the design value for allowable vapor velocity is usually estimated to be 50 to 70 per cent of the maximum allowable velocity, and this allowable velocity is used to establish the column diameter.

General Correlation for Flooding Rate. Figure 16-17 presents a correlation for flooding conditions in packed towers.*† The flooding line for random packings is based on experimental data obtained with 15 different liquids, 3 gases, and various random packings, such as Raschig rings, Berl saddles, spheres, and helices. Best results are obtained if the value of the packing factor (a_p/ϵ^3) is based on direct experimental measurements with the particular packed tower; however, in the absence of experimental values, the data given in Table 3 can be used to approximate a_p/ϵ^3.

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* The correlation presented in Fig. 16-17 is based on the method proposed by T. K. Sherwood, G. H. Shipley, and F. A. L. Holloway, *Ind. Eng. Chem.*, **30**:765 (1938), with the modification of experimental determination of appropriate a_p/ϵ^3 values as given by Lobo et al., *Trans. AIChE*, **41**:693 (1945).

† Many other correlations for flooding rates in packed towers have been proposed. Some examples follow: The results of B. C. Sakiadis and A. I. Johnson, *Ind. Eng. Chem.*, **46**:1229 (1954), apply to spray columns and packed towers. E. H. Hoffing and F. J.

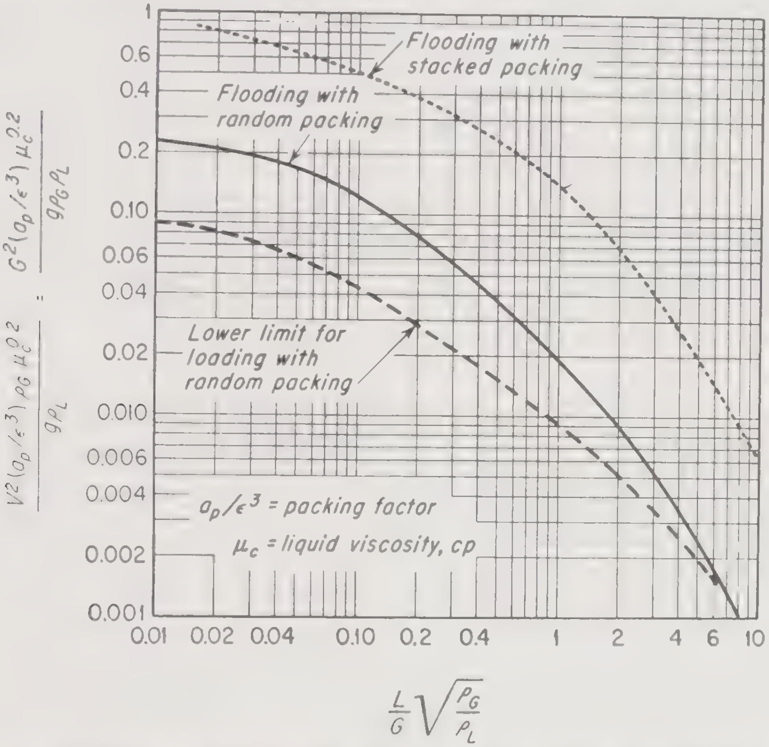

FIG. 16-17. Correlation for estimating flooding rate with gas-liquid systems in packed towers.

The dashed line in Fig. 16-17 represents the approximate lower limit of the loading range for random packings and can be used as a rough check to determine what per cent of the maximum allowable velocity will give operating conditions in the preloading range.* As indicated by the dotted line in Fig. 16-17, stacked packings have higher flow capacities than random packings.† This increased capacity can be attributed partly to the de-

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Lockhart, *Chem. Eng. Progr.*, **50**:94 (1954); F. R. Dell and H. R. C. Pratt, *Trans. Inst. Chem. Engrs. (London)*, **29**:89 (1951), and *J. Appl. Chem.*, **2**:429 (1952), have presented correlations for liquid-liquid and gas-liquid systems.

* M. Leva, *Chem. Eng. Progr., Symposium Ser.*, **50**(10):51 (1954). Leva states that the correlation presented in Fig. 16-17 is improved if the ordinate group is multiplied by $(\rho_{water}/\rho_L)^2$.

† M. C. Molstad et al., *Trans. AIChE*, **38**:405 (1942).

creased holdup and lower pressure drop due to the regular arrangement of the packing.

Simplified Approximate Method for Estimating Flooding Velocities in Packed Distillation Towers.* At the flooding velocity in a packed tower, liquid starts to build up over the packing. It can be assumed, therefore, that flooding occurs when the downward pressure of the descending films or droplets equals the upward velocity pressure of the rising vapor. With this assumption and considering the gas density as negligible in comparison to the liquid density, the pressure-balance equation can be written as

$$\left(\frac{V_m{}^2}{2g}\right)\rho_G = H_p\rho_L \tag{21}$$

where H_p is a constant for each packing and can be considered as the mean diameter or film length of the liquid droplets. If K_p is defined as $(2gH_p)^{0.5}$, Eq. (21) can be expressed in a form similar to Eq. (14) as

$$V_m = K_p\sqrt{\frac{\rho_L}{\rho_G}} \tag{22}$$

Since the superficial gas mass velocity equals $V\rho_G$, Eq. (22) can be written in the following alternative form:

$$G_m = V_m\rho_G = K_p\sqrt{\rho_L\rho_G} \tag{23}$$

Equations (21) through (23) do not include any effects due to liquid viscosity or liquid flow rate. Consequently, the equations are most useful when experimental data for the packing are available at known L/G ratios and liquid viscosities. For design purposes, liquid-viscosity effects can be assumed negligible if the viscosity is under 2 centipoises. Because of errors that may be introduced by neglecting the influence of the liquid rate, use of Eq. (22) or (23) should be limited to cases in which the liquid rate is less than 1.5 times the gas rate.

Effect of Operating Pressure on Flooding Velocities. Because many packed towers are operated at reduced pressures, the effect of total operating pressure on flooding rates is of particular interest to both the design engineer and the operations engineer. As a rough rule of thumb, the maximum allowable vapor velocity V_m in packed distillation columns is from 1 to 3 fps at atmospheric pressure and increases with decreasing pressure in direct proportion to the square root of the pressure ratios. Similarly, the maximum allowable mass velocity G_m decreases with decreasing pressure in direct proportion to the square root of the pressure ratios. A typical example of the effect of operating pressure on maximum allowable vapor velocity and maximum allowable gas mass velocity is presented in Fig. 16-18.

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* M. S. Peters and M. R. Cannon, *Ind. Eng. Chem.*, **44**:1452 (1952).

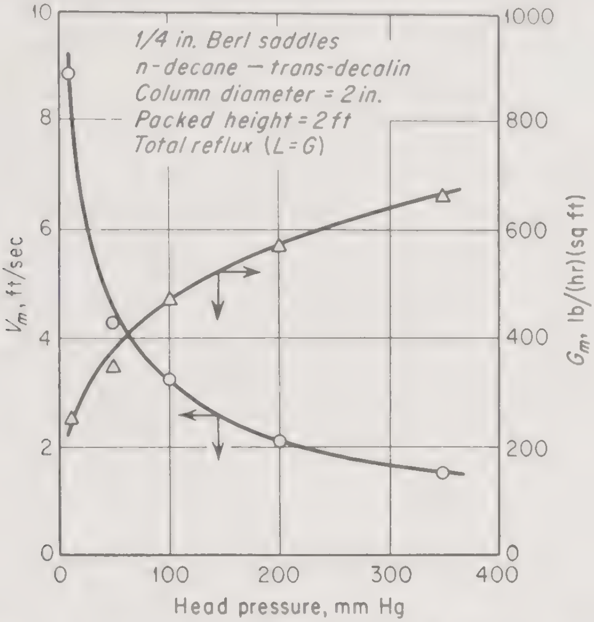

FIG. 16-18. Effect of operating pressure in packed distillation column on maximum allowable gas rates as superficial linear velocity and mass velocity.

The relationship between the maximum allowable rates in a packed distillation tower at two different pressures for a given packing, reflux ratio, and set of fluids can be estimated by writing Eq. (22) or Eq. (23) for each pressure and eliminating the constant K_p. This procedure gives

$$V_{m_1} = V_{m_2}\sqrt{\frac{\rho_{G_2}\rho_{L_1}}{\rho_{G_1}\rho_{L_2}}} \tag{24}$$

$$G_{m_1} = G_{m_2}\sqrt{\frac{\rho_{G_1}\rho_{L_1}}{\rho_{G_2}\rho_{L_2}}} \tag{25}$$

where subscript 1 designates average conditions at one operating pressure and subscript 2 designates average conditions at the second operating pressure.

If the vapor acts as a perfect gas, $\rho_G = M_GP/RT$, and Eqs. (24) and (25) can be expressed as

$$V_{m_1} = V_{m_2}\left(\frac{P_2}{P_1}\right)^{0.5}\left(\frac{\rho_{L_1}}{\rho_{L_2}}\right)^{0.5}\left(\frac{T_1}{T_2}\right)^{0.5}\left(\frac{M_{G_2}}{M_{G_1}}\right)^{0.5} \tag{26}$$

$$G_{m_1} = G_{m_2}\left(\frac{P_1}{P_2}\right)^{0.5}\left(\frac{\rho_{L_1}}{\rho_{L_2}}\right)^{0.5}\left(\frac{T_2}{T_1}\right)^{0.5}\left(\frac{M_{G_1}}{M_{G_2}}\right)^{0.5} \tag{27}$$

where R = perfect-gas-law constant
P = total pressure
T = absolute temperature
M_G = molecular weight of gas .

Example 6. Estimation of Maximum Allowable Gas Rate in Packed Tower. A random-packed distillation tower is being operated at an average pressure equal to 1 atm. The reflux ratio is such that an average value of 1.0 may be assumed for L/G. The column is being operated at 60 per cent of the maximum allowable gas rate. Under these conditions, the average gas rate through the tower is 100 lb/hr and the average superficial gas velocity is 1.5 fps. If the operating pressure is reduced until the average pressure in the tower is 100 mm Hg and the ratio L/G is unchanged, estimate the maximum allowable gas rate as pounds per hour by (*a*) use of the simplified approximate Eq. (23), and (*b*) use of Fig. 16-17. The following data apply:

	At average temperature and atmospheric pressure	At average temperature and 100 mm Hg
ρ_G, lb/cu ft	0.20	0.031
ρ_L, lb/cu ft	50	52
μ_c, centipoises	0.5	0.7

Solution

(*a*) By Eq. (23)

$$G_m = K_p\sqrt{\rho_L\rho_G}$$

At a pressure of 1 atm

$$G_m = \frac{100}{(0.60)(\text{cross-sectional area})} \text{ lb/(hr)(sq ft)}$$

$$K_p = \frac{100}{(0.60)(\text{cross-sectional area})[(50)(0.20)]^{1/2}}$$

At pressure = 100 mm Hg

$$G_m = K_p\sqrt{\rho_L\rho_G} = \frac{(100)[(52)(0.031)]^{1/2}}{(0.60)(\text{cross-sectional area})[(50)(0.20)]^{1/2}}$$

Maximum allowable gas rate at 100 mm Hg pressure by Eq. (23) is

$$G_m(\text{cross-sectional area}) = \frac{100}{0.60}\sqrt{\frac{(52)(0.031)}{(50)(0.20)}} = 67 \text{ lb/hr}$$

The same result could be obtained directly from Eq. (25).

(*b*) At pressure = 1 atm

$$\frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}} = (1)\sqrt{\frac{0.20}{50}} = 0.063$$

From Fig. 16-17

$$\frac{V_m^2(a_p/\epsilon^3)\rho_G\mu_L^{0.2}}{g\rho_L} = 0.15$$

$$V_m = \frac{1.5}{0.60} = 2.5 \text{ fps}$$

$$\frac{a_p}{\epsilon^3} = \frac{(0.15)(32.17)(50)}{(2.5)^2(0.20)(0.5)^{0.2}} = 222$$

At a pressure of 100 mm Hg

$$\frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}} = (1)\sqrt{\frac{0.031}{52}} = 0.024$$

From Fig. 16-17

$$\frac{V_m^2(a_p/\epsilon^3)\rho_G\mu_L^{0.2}}{g\rho_L} = 0.20$$

$$V_m = \left[\frac{(0.20)(32.17)(52)}{(222)(0.031)(0.7)^{0.2}}\right]^{1/2} = 7.2 \text{ fps}$$

$$\text{Cross-sectional area of empty tower} = \frac{100}{(1.5)(0.20)(3600)} = 0.0927 \text{ sq ft}$$

Maximum allowable gas rate at 100 mm Hg by Fig. 16-17 is

$$V_m\rho_G(\text{cross-sectional area}) = (7.2)(0.031)(0.0927)(3600) = 74 \text{ lb/hr}$$

RELATIVE MERITS OF PLATE AND PACKED TOWERS

The choice between use of a plate tower or a packed tower for a given mass-transfer operation should, theoretically, be based on a detailed cost analysis for the two types of contactors. Thus, the optimum economic design for each type would be developed in detail, and the final choice would be based on a consideration of costs and profits at the optimum conditions. In many cases, however, the decision can be made on the basis of a qualitative analysis of the relative advantages and disadvantages, and the need for a detailed cost comparison is eliminated. The following general advantages and disadvantages of plate and packed towers should be considered when a choice must be made between the two types of contactors:

1. Stage efficiencies for packed towers must be based on experimental tests with each type of packing. The efficiency varies, not only with the type and size of packing, but also with the fluid rates, the fluid properties,

the column diameter, the operating pressure, and, in general, the extent of liquid dispersion over the available packing surface.

2. Because of liquid-dispersion difficulties in packed towers, the design of plate towers is considerably more reliable and requires less safety factor when the ratio of liquid mass velocity to gas mass velocity is low.

3. Plate towers can be designed to handle wide ranges of liquid rates without flooding.

4. If the operation involves liquids that contain dispersed solids, use of a plate tower is preferred because the plates are more accessible for cleaning.

5. Plate towers are preferred if interstage cooling is required to remove heats of reaction or solution, because cooling coils can be installed on the plates or the liquid-delivery line from plate to plate can be passed through an external cooler.

6. The total weight of a dry plate tower is usually less than that of a packed tower designed for the same duty. However, if liquid holdup during operation is taken into account, both types of towers have about the same weight.

7. When large temperature changes are involved, as in distillation operations, plate towers are often preferred because thermal expansion or contraction of the equipment components may crush the packing.

8. Design information for plate towers is generally more readily available and more reliable than that for packed towers.

9. Random-packed towers are seldom designed with diameters larger than 4 ft, and diameters of commercial plate towers are seldom less than 2 ft.

10. Packed towers prove to be cheaper and easier to construct than plate towers if highly corrosive fluids must be handled.

11. Packed towers are usually preferred if the liquids have a large tendency to foam.

12. The amount of liquid holdup is considerably less in packed towers.

13. The pressure drop through packed towers may be less than the pressure drop through plate towers designed for the same duty. This advantage, plus the fact that the packing serves to lessen the possibility of tower-wall collapse, makes packed towers particularly desirable for vacuum operation.

COSTS FOR MASS-TRANSFER EQUIPMENT

Plate and Packed Towers

The purchased cost for plate and packed towers can be divided into the following components: (1) cost for shell, including heads, skirts, manholes, and nozzles; (2) cost for internals, including trays and accessories, packing, supports, and distributor plates; (3) cost for auxiliaries, such as platforms, ladders, handrails, and insulation.

Table 6. Cost per Pound for Fabricated Steel Towers *

The indicated costs are for the fabricated tower shell only, without trays, packing, or connections.

Total weight of shell, lb	*Purchase cost of shell, cents/lb (January, 1957)*
1,000	60
5,000	50
10,000	40
20,000	30
50,000	20

* H. Bliss, *Chem. Eng.*, **54**(5):126, **54** (6):100 (1947); W. L. Nelson, *Oil Gas J.*, **47**:113 (Dec. 16, 1948); and O. T. Zimmerman and I. Lavine, "Chemical Engineering Costs," Industrial Research Service, Dover, N.H., 1950.

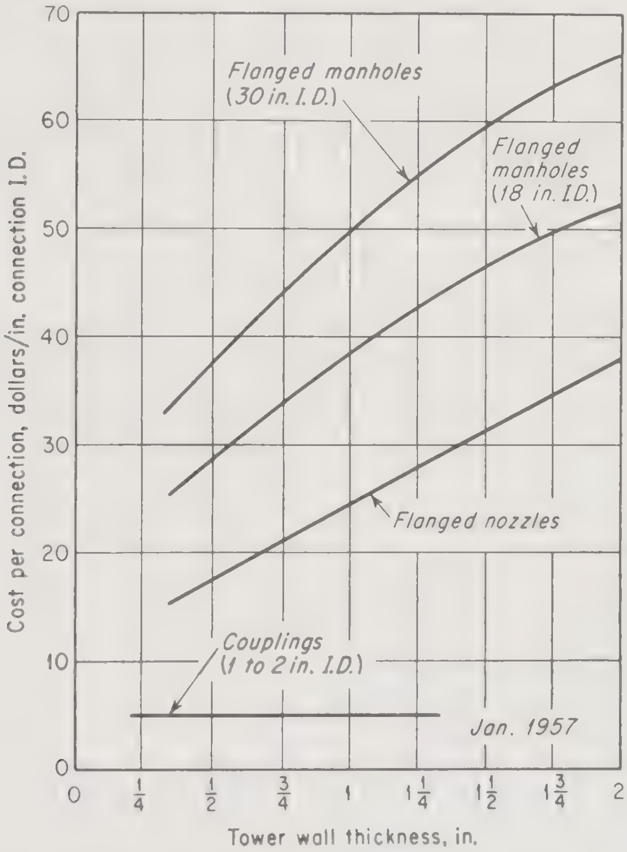

Fig. 16-19. Approximate installed cost of steel tower connections. Values apply to 300-lb connections. Multiply costs by 0.9 for 150-lb connections and by 1.2 for 600-lb connections. [*H. Bliss, Chem. Eng.*, **54**(5):126, **54** (6):100 (1947); *W. L. Nelson, Oil Gas J.*, **47**:113 (Dec. 16, 1948); *O. T. Zimmerman and I. Lavine, "Chemical Engineering Costs," Industrial Research Service, Dover, N.H.*, 1950.]

Shell cost is most conveniently estimated on the basis of weight. Table 6 indicates approximate costs per pound for fabricated steel towers, and the values in this table can be used to obtain a rough estimate of the cost for the fabricated shell without connections. The cost for installed connections, such as manholes and nozzles, can be estimated from the data in Fig. 16-19.

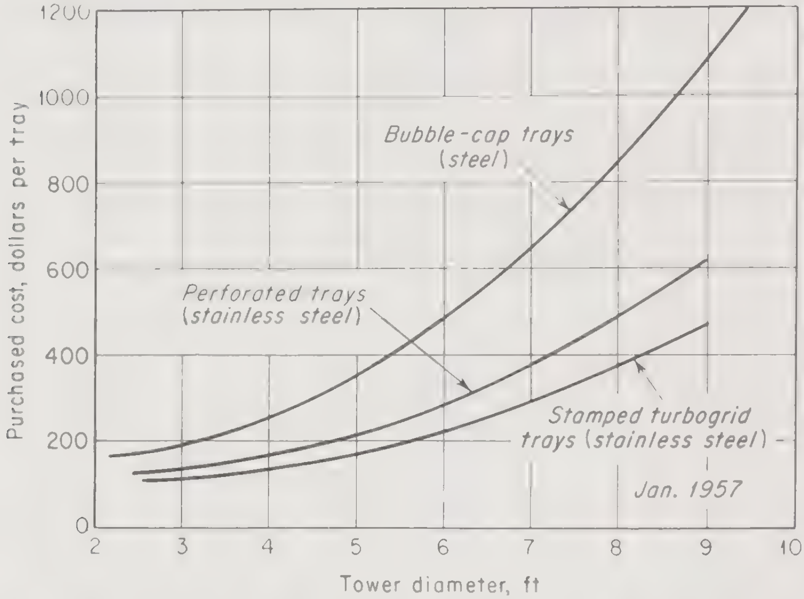

FIG. 16-20. Cost of trays in plate towers, including tray deck, bubble caps, risers, downcomers, structural-steel parts, and tray-installation cost. [*R. S. Aries and R. D. Newton, "Chemical Engineering Cost Estimation," McGraw-Hill Book Company, Inc., New York*, 1955; *H. Bliss, Chem. Eng.*, **54**(5):126, **54**(6):100 (1947); *C. H. Chilton, Chem. Eng.*, **56**(6):97 (1949); *R. Katzen, Chem. Eng.*, **62**(11):209 (1955); *W. L. Nelson, Oil Gas J.*, **47**:277 (Dec. 30, 1948); *Shell Development Co. Eng. Staff, Chem. Eng. Progr.*, **50**:57 (1954); *Petroleum Refiner*, **31**(11):105 (1952); *O. T. Zimmerman and I. Lavine, "Chemical Engineering Costs," Industrial Research Service, Dover, N.H.*, 1950.]

Tray costs are shown in Fig. 16-20 for conventional installations, and the approximate price for various types and sizes of industrial packings is indicated in Fig. 16-21. For rough estimates, the cost for a distributor plate in a packed tower can be assumed to be the same as that for one bubble-cap tray.

Table 7 presents data that can be used for estimating the cost of auxiliaries, such as insulation, ladders, platforms, and handrails. Relative fabricated costs for various materials used in tray-tower construction are listed in Table 8.

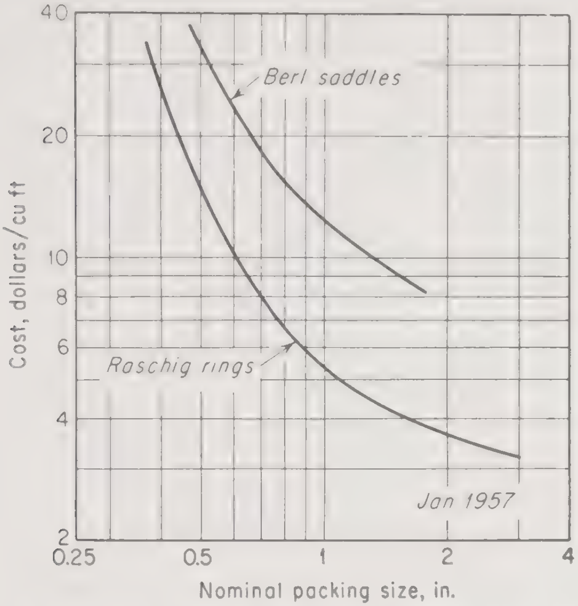

FIG. 16-21. Cost of industrial packings. [*H. Bliss, Chem. Eng.*, **54**(5):126, **54**(6):100 (1947); *W. L. Nelson, Oil Gas J.*, **47**:277 (Dec. 30, 1948); *J. H. Perry, "Chemical Engineers' Handbook,"* 3d *ed., McGraw-Hill Book Company, Inc., New York,* 1950; *O. T. Zimmerman and I. Lavine, "Chemical Engineering Costs," Industrial Research Service, Dover, N.H.*, 1950.]

TABLE 7. COST OF TOWER AUXILIARIES *

Item	Cost, January, 1957	Amount for typical tower	
Ladder	$0.17/lb	30 lb/ft of height	
Platforms and handrails	0.17/lb	Tower diameter, ft	Weight, lb
		4	1700
		6	2300
		8	2800
		10	3300
Insulation	1.80/sq ft 2.40/sq ft	For 1½-in. thickness For 5-in. thickness	

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* H. Bliss, *Chem. Eng.*, **54**(5):126, **54**(6):100 (1947).

TABLE 8. RELATIVE FABRICATED COST FOR METALS USED IN TRAY-TOWER CONSTRUCTION *

Materials of construction	*Relative cost per sq ft of tray area † (based on carbon steel = 1)*
Sheet-metal trays:	
Steel	1
4–6% chrome—½ moly alloy steel	2
11–13% chrome type 410 alloy steel	2.5
Red brass	3
Stainless steel type 304	3
Stainless steel type 347	3.5
Monel	4
Stainless steel type 316	5
Inconel	5
Cast-iron trays	2.8

* J. A. Davies, *Petroleum Refiner*, **29**(8):93 (1950); and J. Donavon, *Chem. Eng. Progr.*, **50**:320 (1954).

† These factors on a per-pound basis also apply approximately to the fabricated materials used for the tower shell.

DRYERS

Cost data for drum dryers and rotary dryers are presented in Fig. 16-22. Additional cost data and an outline of design methods for dryers are covered in two extensive articles by Lapple, Clark, and Dybdal.*

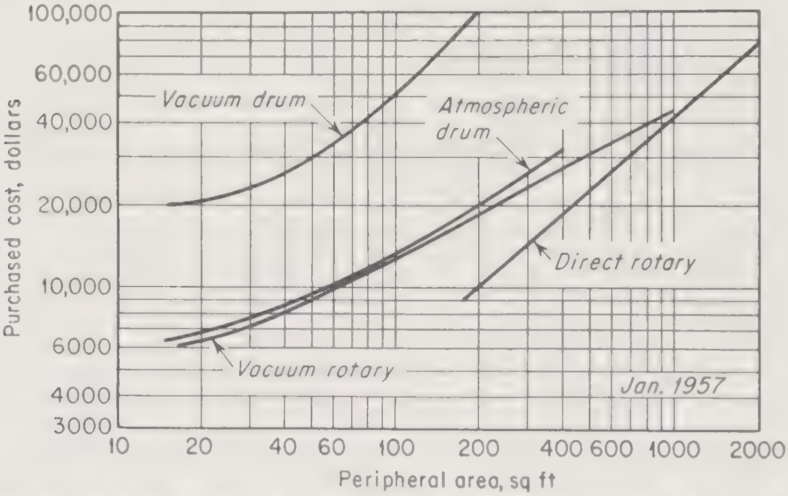

FIG. 16-22. Cost of steel rotary and drum dryers with auxiliaries. [*R. S. Aries and R. D. Newton, "Chemical Engineering Cost Estimation," McGraw-Hill Book Company, Inc., New York,* 1955; *G. J. Crites, Chem. Eng. Costs Quarterly,* **6**:4 (1956); *W. C. Lapple, W. E. Clark, and E. C. Dybdal, Chem. Eng.,* **62**(11):177 (1955); *J. F. Maguire, Chem. Eng. Costs Quarterly,* **6**:37 (1956); *J. H. Perry, "Chemical Engineers' Handbook," 3d ed., McGraw-Hill Book Company, Inc., New York,* 1950.]

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* W. C. Lapple, W. E. Clark, and E. C. Dybdal, *Chem. Eng.*, **62**(11):177; **62**(10):191 (1955).

Example 7. Estimation of Cost for Bubble-cap Tower. A distillation tower contains 18 steel bubble-cap trays. An 18-in. manhole is located above each tray, and one manhole is located below the bottom tray. The ID of the tower is 6 ft, and the total height including the skirt is 50 ft. The shell is steel (density = 490 lb/cu ft) with a $\frac{5}{8}$-in. wall thickness. Six 1-in. couplings and the following flanged nozzles are attached to the tower: one 10-in. vapor-line nozzle; three 4-in. nozzles; and six 2-in. nozzles. On the basis of the data presented in Table 6, Fig. 16-19, and Fig. 16-20, estimate the cost of the tower with trays installed, but not including cost for auxiliaries or tower installation. The total weight of the shell, including heads and skirt, may be assumed to be 1.12 times the weight of the cylindrical shell.

Solution

$$\text{Total weight of shell} = (6)(\tfrac{5}{8})(\tfrac{1}{12})(3.14)(50)(490)(1.12) = 27{,}000 \text{ lb}$$

Purchased cost of steel shell = (27,000)(0.28)	$ 7,600
Cost for 19 installed 18-in. manholes = (19)(31)(18)	10,600
Cost for 1 installed 10-in. nozzle = (1)(19)(10)	190
Cost for 3 installed 4-in. nozzles = (3)(19)(4)	230
Cost for 6 installed 2-in. nozzles = (6)(19)(2)	230
Cost for 6 installed 1-in. couplings = (6)(1)(5)	30
Cost for 18 installed steel bubble-cap trays = (18)(490)	8,800
Total	$27,680

Estimated total purchased cost for tower = $28,000

According to W. L. Nelson, *Oil Gas J.*, **47**:93 (Jan. 6, 1949), the estimated total purchased cost for the distillation tower described in this problem was $16,000 in 1946.

NOMENCLATURE FOR CHAP. 16

a_p = surface area of packing per unit of packed-tower volume, sq ft/cu ft

A_d = minimum cross-sectional area for downcoming liquid flow in plate tower, sq ft

b = width of slot at base, ft

c = height of slot, ft

C_D = liquid gradient factor; see Fig. 16-8

d_p = effective diameter of packing particle, ft; defined with Eq. (20)

d_{wc} = perpendicular distance from weir to center of tower, ft

D = inside diameter of tower, ft

E_o = over-all column efficiency, per cent

F_C = correction factor for evaluation of liquid gradient; see Fig. 16-8

g = local acceleration due to gravity; usually taken as 32.17 ft/(sec)(sec)

g_c = conversion factor in Newton's law of motion, 32.17 ft-lb mass/(sec)(sec)(lb force)

G = superficial mass velocity of gas (based on cross-sectional area of empty tower), lb/(hr)(sq ft)

G_m = maximum allowable superficial mass velocity of gas (based on cross-sectional area of empty tower) lb/(sec)(sq ft) or lb/(hr)(sq ft)

h = packed height, ft

h_r = head of liquid equivalent to pressure drop due to gas flow through riser and cap, ft of liquid

h_d = head of liquid equivalent to pressure drop due to liquid flow through downcomer and constriction, ft of liquid
h_g = liquid gradient across tray, ft
h_H = head of liquid equivalent to pressure drop due to one kinetic head, ft of liquid
h_o = head of liquid over weir, ft
h_{slot} = distance liquid is depressed below top of slot = head of liquid equivalent to pressure drop due to gas flow through slots, ft of liquid
h_T = head of liquid equivalent to total pressure drop of gas across tray, ft of liquid
h_w = height of weir, ft
H = total head of liquid in downcomer, ft
H_p = a constant for evaluating maximum allowable gas rates in packed towers, ft
K_p = a constant for evaluating maximum allowable gas rates in packed towers, fps
K_v = a constant for evaluating maximum allowable gas rates in bubble-cap towers, fps
l_c = total free space between bubble caps perpendicular to direction of liquid flow, average of various rows, ft
l_r = total free space between bubble-cap risers perpendicular to direction of liquid flow, average of various rows, ft
l_w = weir length, ft
L = superficial mass velocity of liquid (based on cross-sectional area of empty tower), lb/(hr)(sq ft)
L'_M = molal liquid flow rate, lb mole/hr
m_{avg} = mole fraction of solute in gas in equilibrium with liquid/mole fraction of solute in liquid at average column temperature and pressure
M_A = average molecular weight of liquid absorbent, lb
M_G = molecular weight of gas, lb
p = pressure; Δp is pressure drop in packed tower, psf or in. water
p_F = pressure at flooding; Δp_F is pressure drop in packed column at flooding point, psf or in. water
p_T = pressure; Δp_T is total pressure drop of gas across bubble-cap tray, psi
P = total pressure, expressed as equivalent ft of liquid or psf
Q_L = volumetric flow rate of liquid, cfs
Q_s = volumetric flow rate of gas, cfs
r = number of rows of caps perpendicular to direction of liquid flow
R = perfect-gas-law constant, 1545 psf–cu ft/(lb mole)(°R)
s = skirt clearance, ft
S_m = static submergence, distance from top of bubble-cap slot to liquid surface when liquid is just ready to flow over the weir, ft
T = absolute temperature, °R
V = superficial linear velocity of gas (based on cross-sectional area of empty tower), fps
V_c = linear velocity of gas in riser, reversal area, or annulus of bubble cap (maximum value), fps
V_m = maximum allowable superficial linear velocity of gas (based on cross-sectional area of empty tower), fps
V'_M = molal gas flow rate, lb mole/hr
W_T = average width of tray normal to direction of liquid flow (computed as the average of the total tray width at each row of caps), ft

Greek Symbols

α_{avg} = alpha, relative volatility of key components at average column temperature and pressure

α_s, α_s' = quantities for evaluating pressure drop through slots; defined in footnote to Eqs. (5) and (6)

β_s, β_s' = beta, quantities for evaluating pressure drop through slots; defined in footnote to Eqs. (5) and (6)

γ = gamma, constant, value dependent on packing size and type; see Table 4

ϵ = epsilon, fractional void volume in packed bed, cu ft void/cu ft of packed-tower volume

θ = theta, angle subtended from center of tower by chord weir, deg

$\mu_{A,\text{avg}}$ = mu, molal average viscosity of liquid absorbent at average column temperature and pressure, centipoises

μ_c = absolute viscosity of liquid, centipoises

$\mu_{F,\text{avg}}$ = molal average viscosity of feed at average column temperature and pressure, centipoises

μ_G = absolute viscosity of gas, lb/(ft)(hr)

π = pi, constant = 3.1416

$\rho_{A,\text{avg}}$ = rho, density of liquid absorbent at average column temperature and pressure, lb/cu ft

ρ_G = gas density, lb/cu ft

ρ_L = liquid density, lb/cu ft

σ = sigma, surface tension of liquid, dynes/cm

Φ = phi, constant, value dependent on packing size and type; see Table 4

PROBLEMS

1. A sieve-tray tower has an ID of 5 ft, and the combined cross-sectional area of the holes on one tray is 10 per cent of the total cross-sectional area of the tower. The height of the weir is 1.5 in. The head of liquid over the top of the weir is 1 in. Liquid gradient is negligible. The diameter of the perforations is $^3/_{16}$ in., and the superficial vapor velocity (based on the cross-sectional area of the empty tower) is 3.4 fps. The pressure drop due to passage of gas through the holes may be assumed to be equivalent to 1.4 kinetic heads (based on gas velocity through holes). If the liquid density is 50 lb/cu ft and the gas density is 0.10 lb/cu ft, estimate the pressure drop per tray as pounds force per square inch.

2. An existing bubble-cap distillation tower has an ID of 8 ft and a tray spacing of 30 in. The tower is operating under a pressure of 70 psig, and a slot liquid seal of 2 in. is maintained. At the point of maximum volumetric vapor flow, the molecular weight of the vapor is 100, the rate of vapor flow is 1500 lb mole/hr, the liquid density is 55 lb/cu ft, and the temperature is 175°F. The pressure drop through the tower is negligible, and the perfect-gas law is applicable to the rising vapors. Approximately what per cent of the maximum allowable flow rate is being used in the tower?

3. A mixture of benzene and toluene containing 60 mole % benzene is to be separated into an overhead product containing 96 mole % benzene and a bottoms containing 25 mole % benzene. A bubble-cap tower has been designed which is intended to accomplish this separation at atmospheric pressure. At the operating conditions chosen, calculations have shown that 6.1 theoretical stages are necessary. The temperature is 181°F at the top of the column and 213°F in the reboiler. Assuming the reboiler acts as one theoretical stage, estimate the number of actual trays required. Benzene and toluene mixtures may be considered as ideal. At 197°F, the vapor pressure of pure benzene is 1070 mm Hg and the vapor pressure of pure toluene is 429 mm Hg.

4. For the conditions given in Example 2, what weir height would be necessary to reduce the following dimensionless ratio to the recommended maximum value of 0.4: liquid gradient/pressure-drop head caused by bubble-cap assemblies?

5. Air is passing through a bubble-cap plate at a superficial vapor velocity of 2 fps. Water is flowing across the tray at a rate of 0.1 cu ft/(sec)(ft diameter). The water and air are at a temperature of 70°F, and the pressure is 1 atm. Assuming stable operation of the plate and a liquid gradient of 0.4 in., estimate the per cent of the total pressure drop across the tray due to the head of liquid above the slots. The following specifications apply to the unit:

Inside diameter = 6 ft
Minimum total cross-sectional area of riser, direction-reversal space in cap, or annular cap space = 15 per cent of tower cross-sectional area
Total slot area = 10 per cent of tower cross-sectional area
Length of chord weir = 0.7 × tower diameter
Slots in caps are triangular, and slot width at base = 0.4 in.
Slot height = 1.5 in.
Static submergence = 1.0 in.

6. A random-packed absorption tower is to be used for removing a hydrocarbon from a gas mixture by countercurrent scrubbing with an oil. Stoneware Raschig rings of 1-in. nominal size will be used as the packing. The tower must handle a gas rate of 2000 lb/hr and a liquid rate of 6000 lb/hr. A gas velocity equal to 70 per cent of the maximum allowable velocity at the given liquid and gas rates will be used. The gas density is 0.075 lb/cu ft. The liquid density is 55 lb/cu ft. The viscosity of the oil is 20 centipoises. Under these conditions, estimate the necessary tower diameter and the pressure drop through the tower as inches of water per foot of packed height.

7. A blower is being used to force 200 lb of air per hour through a 12-in. inside-diameter tower countercurrent to water flowing at a rate of 6000 lb/hr. The tower is packed to a height of 10 ft with 1-in. Berl saddles. The average pressure in the tower is 1 atm, and the temperature is 75°F. The blower-motor combination used at the gas inlet has an over-all efficiency of 50 per cent. Estimate the power cost per 8000 operating hours for forcing the air through the packing if the cost of power is $0.015 per kilowatthour.

8. A random-packed distillation tower with an inside diameter of 6 in. is being operated at a condenser pressure of 100 mm Hg. The following data are obtained during operation:

Packed height = 3 ft
Gas rate = 100 lb/hr
Liquid rate = 90 lb/hr
Average molecular weight of gas = 100
Average temperature = 110°F
Total pressure drop = 12 mm Hg
Liquid viscosity = 1.2 centipoises
Liquid density = 55 lb/cu ft

A larger distillation tower is needed for the same mixture, and it has been decided to use a 12-in. inside-diameter tower with the same type and size of packing. The packed height will be 3 ft. The condenser pressure will be 50 mm Hg, and the average temperature can be assumed to be 95°F. At this temperature, the liquid viscosity is

1.4 centipoises, the liquid density 57 lb/cu ft. The 12-in. tower will be operated at the same per cent of the maximum allowable gas mass velocity as the 6-in. tower, and the same ratio of L/G will be used. The average molecular weight of the gas is unchanged. With the given packing and fluids, the pressure drop at the flooding point can be assumed to be 16 mm Hg/ft of packed height. Neglecting the effect of temperature on fluid densities at the flooding point, estimate the gas rate as pounds per hour at the indicated operating conditions in the 12-in. tower.

9. A special test on the 6-in. distillation tower described in Prob. 8 indicates that the total pressure drop is 2.9 mm Hg when the gas rate is 50 lb/hr. For this test, the condenser pressure was maintained at 100 mm Hg, the L/G ratio was the same as shown in Prob. 8, and temperature change was negligible. Operation can be considered to be under preloading conditions. Estimate the total pressure drop at the operating conditions indicated in Prob. 8 for the 12-in. column.

10. A random-packed tower is to be used for contacting 3000 lb/hr of air with 4000 lb/hr of water. The tower will be packed with 1-in. Raschig rings. The operating pressure is 1 atm, and the temperature is 70°F. Assuming column operation is in the preloading range, estimate the optimum diameter per foot of packed height to give minimum annual cost for fixed charges and blower operating charges. The following additional data apply:

Annual fixed charges = 0.2 × cost of installed unit
Cost of installed unit, complete with distributor plates, supports, and all auxiliaries = 2.0 × purchased cost of shell and packing
Purchased cost of shell = \$10/cu ft of packed volume
Purchased cost of packing = \$5.50/cu ft
Cost of delivered power = \$0.02/kwhr
Operating time = 8000 hr/year

CHAPTER 17

FILTERS AND MISCELLANEOUS EQUIPMENT—DESIGN AND COSTS

FILTERS

The primary factor in the design of filters is the cake resistance or cake permeability. Because the value of the cake resistance can be determined only on the basis of experimental data, laboratory or pilot-plant tests are almost always necessary to supply the information needed for a filter design. After the basic constants for the filter cake have been determined experimentally, the theoretical concepts of filtration can be used to establish the effects of changes in operating variables such as filtering area, slurry concentration, or pressure-difference driving force.

In recent years, there has been considerable advance in the development of filtration theory, but the development has not reached the stage where an engineer can design a filter directly from basic equations as he would a fractionation tower or a heat exchanger. Instead, the final design should be carried out by the technical personnel in filtration-equipment manufacturing concerns or by someone who has access to the necessary testing equipment and has an extensive understanding of the limitations of the design equations.

Choice of a filter for a particular operation depends on many factors. Some of the more important of these are:

1. Fixed and operating costs
2. Quantities and value of materials to be handled
3. Properties of the fluid, such as viscosity, density, and corrosive nature
4. Whether the valuable product is to be the solid, the fluid, or both
5. Concentration, temperature, and pressure of slurry
6. Particle size and shape, surface characteristics of the particles, and compressibility of the solid material
7. Extent of washing necessary for the filter cake

Although a wide variety of filters are available on the market, the types can generally be classified as *batch* or *continuous*. A typical batch filter of the plate-and-frame type is illustrated in Fig. 17-1, while a continuous rotary vacuum filter is shown in Figs. 17-2 and 17-3.

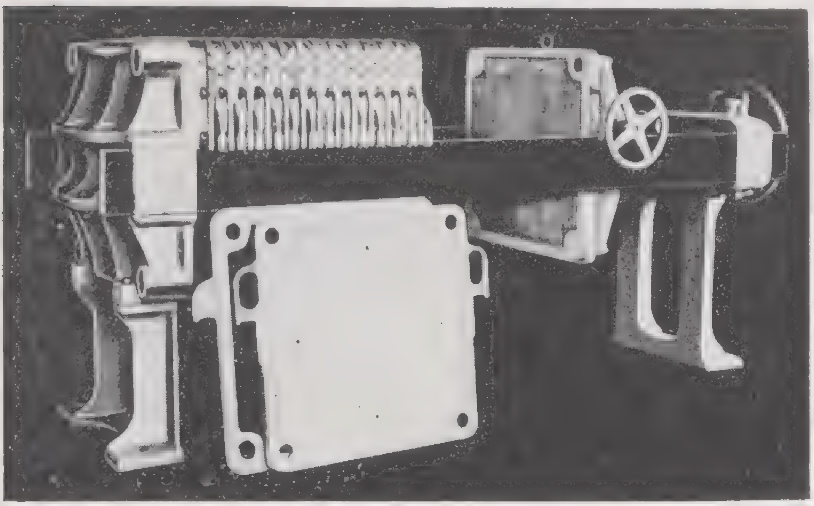

FIG. 17-1. Plate-and-frame filter press. (*Shriver and Company.*)

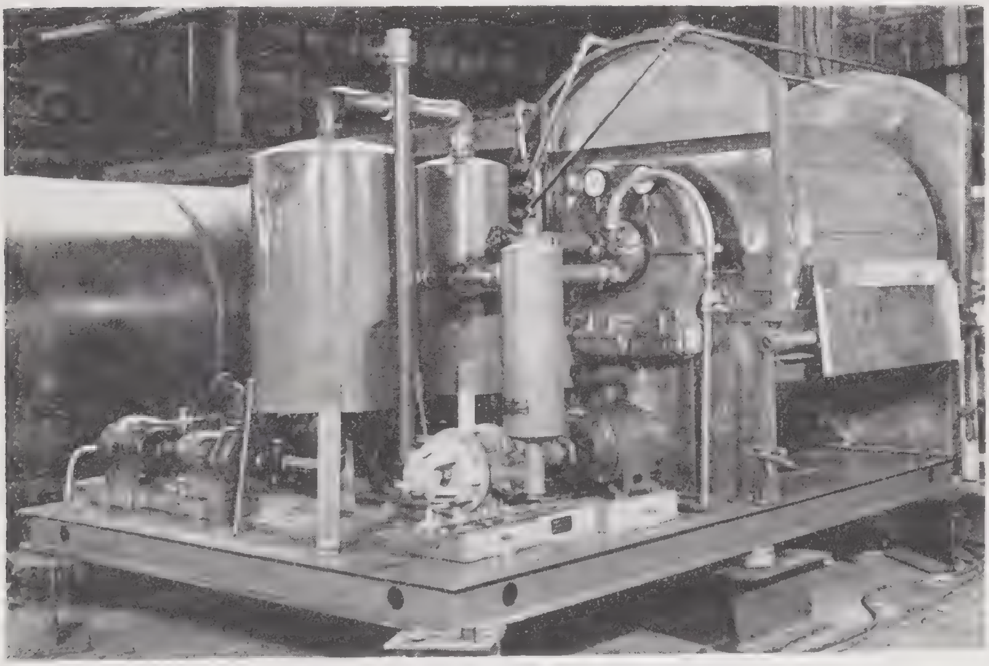

FIG. 17-2. Rotary vacuum-drum filter complete with auxiliaries. (*Eimco Corporation.*)

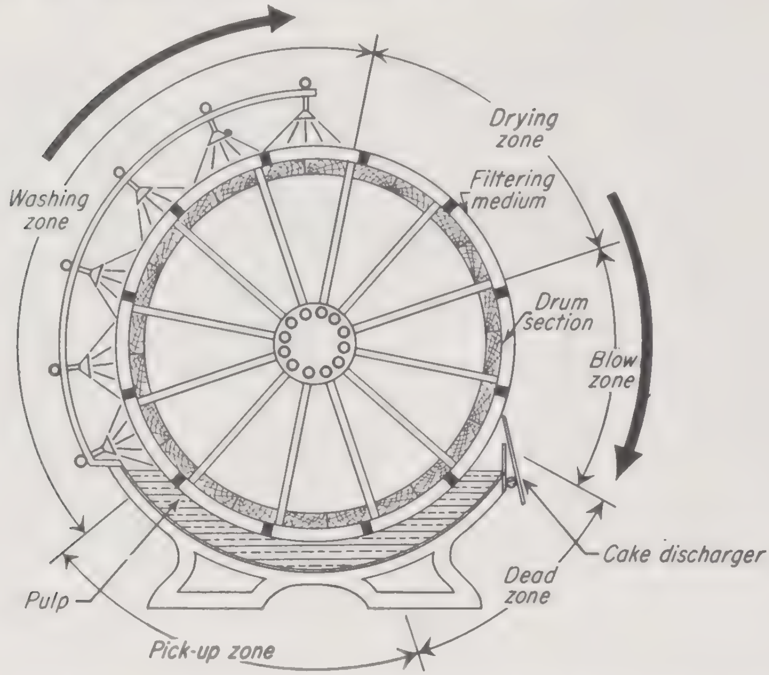

FIG. 17-3. Cross-sectional end view of rotary vacuum-drum filter. (*Eimco Corporation.*)

There are many times when the engineer wishes to make a preliminary design without asking for immediate assistance from a specialist in the field. The theoretical equations presented in the following sections are adequate for this purpose.

Design Equations

The rate at which filtrate is obtained in a filtering operation is governed by the materials making up the slurry and the physical conditions of the operation. The major variables that affect the filtration rate are:

1. Pressure drop across the cake and the filter medium
2. Area of the filtering surface
3. Viscosity of the filtrate
4. Resistance of the cake
5. Resistance of the filter medium

The rate of filtrate delivery is inversely proportional to the combined resistance of the cake and filtering medium, inversely proportional to the viscosity of the filtrate, and directly proportional to the available filtering area and the pressure-difference driving force. This statement can be expressed in equation form as

$$\frac{dV}{d\theta} = \frac{A\,\Delta P}{(R_K + R_F)\mu} \tag{1}$$

where V = volume of filtrate delivered in time θ
A = area of the filtering surface
ΔP = pressure drop across filter
R_K = resistance of the cake
R_F = resistance of the filter medium
μ = viscosity of the filtrate

Cake resistance R_K varies directly with the thickness of the cake, and the proportionality can be expressed as

$$R_K = Cl \tag{2}$$

where C = the proportionality constant and l = the cake thickness at time θ.

It is convenient to express R_F in terms of a fictitious cake thickness l_F with resistance equal to that of the filter medium. Thus,

$$R_F = Cl_F \tag{3}$$

Designating w as the pounds of dry-cake solids per unit volume of filtrate, ρ_c as the cake density expressed as pounds of dry-cake solids per unit volume of wet filter cake, and V_F as the fictitious volume of filtrate per unit of filtering area necessary to lay down a cake of thickness l_F, the actual cake thickness plus the fictitious cake thickness is

$$l + l_F = \frac{w(V + AV_F)}{\rho_c A} \tag{4}$$

Equations (1) to (4) can be combined to give

$$\frac{dV}{d\theta} = \frac{A^2\,\Delta P}{\alpha w(V + AV_F)\mu} \tag{5}$$

where α equals C/ρ_c and is known as the *specific cake resistance*. In the usual range of operating conditions, the value of the specific cake resistance can be related to the pressure difference by the empirical equation

$$\alpha = \alpha'\,(\Delta P)^s \tag{6}$$

where α' is a constant with value dependent on the properties of the solid material and s is a constant known as the *compressibility exponent of the cake*. The value of s would be zero for a perfectly noncompressible cake and unity for a completely compressible cake. For commercial slurries, the value of s is usually between 0.1 and 0.8.

The following general equation for rate of filtrate delivery is obtained by combining Eqs. (5) and (6):

$$\frac{dV}{d\theta} = \frac{A^2\,(\Delta P)^{1-s}}{\alpha' w(V + AV_F)\mu} \tag{7}$$

This equation applies to the case of constant-rate filtration. For the more common case of constant-pressure-drop filtration, A, ΔP, s, α', w, V_F, and μ can all be assumed to be constant with change in V, and Eq. (7) can be integrated between the limits of zero and V to give

$$V^2 + 2AV_FV = \frac{2A^2\,(\Delta P)^{1-s}}{\alpha' w \mu}\,\theta \tag{8}$$

Batch Filters. Equations (7) and (8) are directly applicable for use in the design of batch filters. The constants α', s, and V_F must be evaluated experimentally, and the general equations can then be applied to conditions of varying A, ΔP, V, θ, w, and μ. One point of caution is necessary, however. In the usual situations, the constants are evaluated experimentally in a laboratory or pilot-plant filter. These constants may be used to scale up to a similar filter with perhaps 100 times the area of the experimental unit. To reduce scale-up errors, the constants should be obtained experimentally with the same slurry mixture, same filter aid, and approximately the same pressure drop as are to be used in the final designed filter. Under these conditions, the values of α' and s will apply adequately to the larger unit. Fortunately, V_F is usually small enough for changes in its value due to scale-up to have little effect on the final results.

The following example illustrates the methods for determining the constants and applying them in the design of a large plate-and-frame filter.

Example 1. Estimation of Filtering Area Required for a Plate-and-Frame Filtration Operation. A plate-and-frame filter press is to be used for removing the solid material from a slurry containing 5 lb of dry solids per cubic foot of solid-free liquid. The viscosity of the liquid is 1 centipoise, and the filter must deliver at least 400 cu ft of solid-free filtrate over a continuous operating time of 2 hr when the pressure-difference driving force over the filter unit is constant at 25 psi. On the basis of the following data obtained in a small plate-and-frame filter press, estimate the total area of filtering surface required.

EXPERIMENTAL DATA: The following data were obtained in a plate-and-frame filter press with a total filtering area of 8 sq ft:

Total volume of filtrate (V), cu ft	Time from start of filtration (θ), hr, at constant pressure difference of		
	ΔP = 20 psi	ΔP = 30 psi	ΔP = 40 psi
5	0.34	0.25	0.21
8	0.85	0.64	0.52
10	1.32	1.00	0.81
12	1.90	1.43	1.17

The slurry (with filter aid) was identical to that which was to be used in the large filter. The filtrate obtained was free of solid, and a negligible amount of liquid was retained in the cake.

Solution

An approximate solution could be obtained by interpolating for values of V at $\Delta P = 25$ psi and then using two of these values to set up Eq. (8) in the form of two equations involving only the two unknowns V_F and $(\Delta P)^{1-s}/\alpha' w\mu$. By simultaneous solution, the values of V_F and $(\Delta P)^{1-s}/\alpha' w\mu$ could be obtained. The final required area could then be determined directly from Eq. (8). Because this method puts too much reliance on the precision of individual experimental measurements, a more involved procedure using all the experimental data is recommended.

The following method can be used to evaluate the constants V_F, s, and α' in Eq. (8): Rearrange Eq. (8) to give

$$\frac{\theta\,\Delta P}{V/A} = \frac{\alpha' w\mu\,(\Delta P)^s}{2}\,\frac{V}{A} + \alpha' w\mu V_F\,(\Delta P)^s$$

At constant ΔP a plot of $\theta\,\Delta P/(V/A)$ vs. V/A should give a straight line with a slope equal to $\alpha' w\mu(\Delta P)^s/2$ and an intercept at $V/A = 0$ of $\alpha' w\mu V_F\,(\Delta P)^s$. Figure 17-4 presents a plot of this type based on the experimental data for this problem. Any time the same variable appears in both the ordinate and abscissa of a straight-line plot, an analysis for possible misinterpretation should be made. In this case, the values of θ and ΔP change sufficiently to make a plot of this type acceptable.

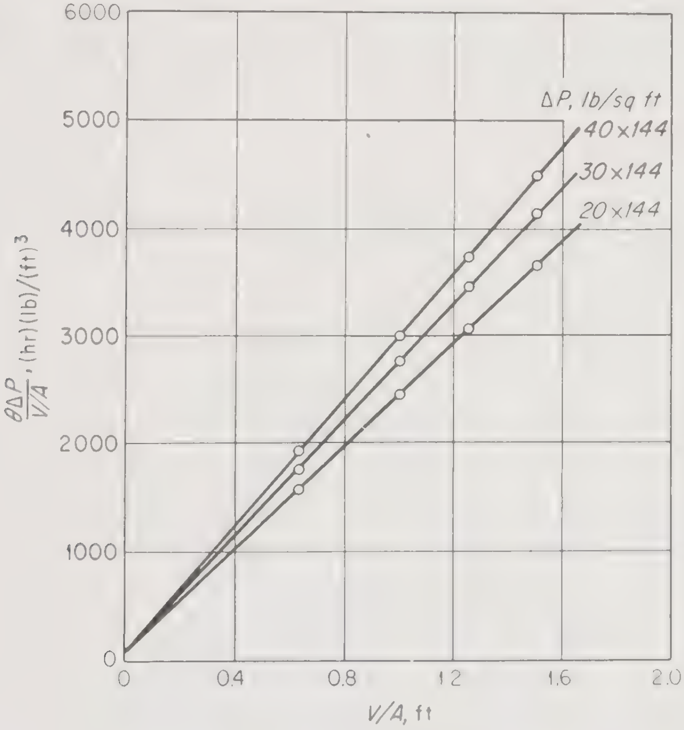

FIG. 17-4. Plot for evaluation of constants for filtrate-rate equation in Example 1.

The following slopes and intercepts are obtained from Fig. 17-4:

ΔP, psf	Slope = $\frac{\alpha' w \mu (\Delta P)^s}{2}$, (hr)(lb)/(ft^4)	Intercept = $\alpha' w \mu V_F (\Delta P)^s$, (hr)(lb)/cu ft
20 × 144	2380	70
30 × 144	2680	80
40 × 144	2920	90

Values of α', s, and V_F could now be obtained by simultaneous solution with any three of the appropriate values presented in the preceding list. However, a better idea as to the reliability of the design constants is obtained by using the following procedure:

Take the logarithm of the expressions for the slope and the intercept in Fig. 17-4. This gives

$$\log (\text{slope}) = s \log \Delta P + \log \frac{\alpha' w \mu}{2}$$

$$\log (\text{intercept}) = s \log \Delta P + \log \alpha' w \mu V_F$$

A log-log plot of the Fig. 17-4 slopes versus ΔP should give a straight line with a slope of s and an intercept at $\log (\Delta P) = 0$ of $\log (\alpha' w \mu/2)$. In this way, s and α' can be evaluated, and the consistency of the data can be checked. This plot is presented in Fig. 17-5. From the slope and intercept,

$$s = 0.3$$

$$\frac{\alpha' w \mu}{2} = 220$$

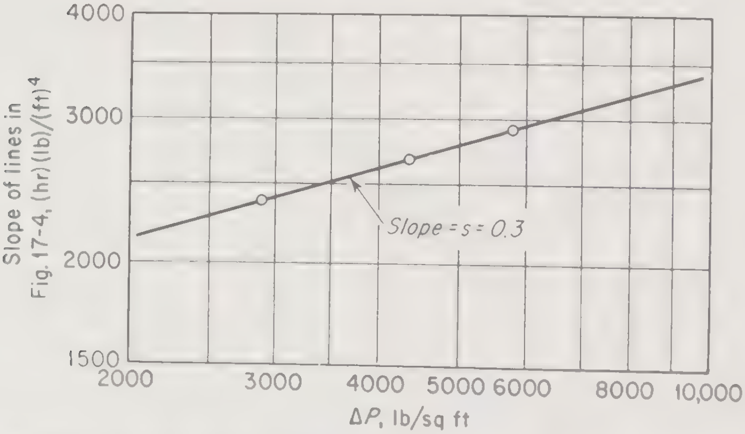

FIG. 17-5. Secondary plot for evaluation of constants for filtrate-rate equation in Example 1.

Similarly, a log-log plot of the Fig. 17-4 intercepts versus ΔP should give a straight line with a slope of s and an intercept at $\log(\Delta P) = 0$ of $\log(\alpha' w \mu V_F)$, from which V_F could be evaluated. Because the value of V_F is relatively small, the intercepts read from Fig. 17-4 are not precise. The value of V_F, therefore, will be estimated from the combined results of Fig. 17-4 and 17-5.

$$w = 5 \text{ lb/cu ft}$$

$$\mu = 2.42 \text{ lb/(hr)(ft)}$$

$$\alpha' = \frac{(220)(2)}{(5)(2.42)} = 36 \text{ with units equivalent to } \alpha \text{ units of hr}^2/\text{lb}$$

On the basis of the Fig. 17-4 intercept for the 30-psi line,

$$V_F = \frac{80}{\alpha' w \mu\,(\Delta P)^s} = \frac{80}{(36)(5)(2.42)(30 \times 144)^{0.3}}$$

$$= 0.015 \text{ cu ft/sq ft}$$

Substitution of the constants into Eq. (8) gives the final equation for use in evaluating the total filtering area needed for the large filter:

$$V^2 + 0.03AV = \frac{2A^2\,(\Delta P)^{1-0.3}}{36 w\mu}\,\theta$$

For the conditions of this problem,

$V = 400$ cu ft
$\Delta P = 25 \times 144$ psf
$w = 5$ lb/cu ft
$\mu = 2.42$ lb/(hr)(ft)
$\theta = 2$ hr

Substituting the indicated values gives

$$(400)^2 + (0.03)(400)A = \frac{2A^2(25 \times 144)^{0.7}(2)}{(36)(5)(2.42)}$$

Solving for A,

$$A = 240 \text{ sq ft}$$

The total area of filtering surface required is approximately 240 sq ft.

Continuous Filters. Many types of continuous filters, such as rotary-drum or rotary-disk filters, are employed in industrial operations. Development of the general design equations for these units follows the same line of reasoning as that presented in the development of Eq. (8). The following analysis is based on the design variables for a typical rotary vacuum filter of the type shown in Figs. 17-2 and 17-3.

It is convenient to develop the design equations in terms of the total area available for filtering service, even though only a fraction of this area is in direct use at any instant. Designate the total available area as A_D and the fraction of this area immersed in the slurry as ψ_f. The effective area of the filtering surface then becomes $A_D\psi_f$, and Eq. (1) can be expressed in the following form:

$$\frac{dV}{d\theta} = \frac{A_D\psi_f\,\Delta P}{(R_K + R_F)\mu} \tag{9}$$

According to Eqs. (2) and (3),

$$R_K + R_F = C(l + l_F) \tag{10}$$

With a continuous filter, the cake thickness at any given location on the submerged filtering surface does not vary with time. The thickness, however, does vary with location as the cake builds up on the filtering surface during passage through the slurry. The thickness of the cake leaving the filtering zone is a function of the slurry concentration, cake density, and volume of filtrate delivered per revolution. This thickness can be expressed by the following equation:

$$l_{\text{leaving filtering zone}} = \frac{wV_R}{\rho_c A_D} \tag{11}$$

where V_R = volume of filtrate delivered per revolution and ρ_c = cake density as pounds of dry-cake solids per unit volume of wet filter cake leaving filter zone.

An average cake thickness during the cake-deposition period can be assumed to be one-half the sum of the thicknesses at the entrance and exit of the filtering zone. Since no appreciable amount of cake should be present on the filter when it enters the filtering zone,

$$l_{\text{avg}} = \frac{wV_R}{2\rho_c A_D} \tag{12}$$

By using the same procedure as was followed in the development of Eq. (4),

$$l + l_F = l_{\text{avg}} + l_F = \frac{w(V_R/2 + A_D\psi_f V_F)}{\rho_c A_D} \tag{13}$$

Combination of Eqs. (9), (10), and (13), with $\alpha = C/\rho_c$, gives

$$\frac{dV}{d\theta} = \frac{2A_D{}^2\psi_f\,\Delta P}{\alpha w(V_R + 2A_D\psi_f V_F)\mu} \tag{14}$$

Integration of Eq. (14) between the limits of $V = 0$ and $V = V_R$, and $\theta = 0$ and $\theta = 1/N_R$, where N_R is the number of revolutions per unit time, gives

$$V_R{}^2 + 2A_D\psi_f V_F V_R = \frac{2A_D{}^2\psi_f\,\Delta P}{\alpha w\mu N_R} \tag{15}$$

or, by including Eq. (6),

$$V_R^2 + 2A_D\psi_f V_F V_R = \frac{2A_D^2\psi_f(\Delta P)^{1-s}}{\alpha' w\mu N_R} \tag{16}$$

The constants in the preceding equations can be evaluated by a procedure similar to that described in Example 1. Equation (16) is often used in the following simplified forms, which are based on the assumptions that the resistance of the filter medium is negligible and the filter cake is noncompressible:

$$\text{Volume of filtrate per revolution} = V_R = A_D\sqrt{\frac{2\psi_f\,\Delta P}{\alpha w\mu N_R}} \tag{17}$$

$$\text{Volume of filtrate per unit time} = V_R N_R = A_D\sqrt{\frac{2\psi_f N_R\,\Delta P}{\alpha w\mu}} \tag{18}$$

$$\text{Weight of dry cake per unit time} = V_R N_R w = A_D\sqrt{\frac{2\psi_f N_R w\,\Delta P}{\alpha\mu}} \tag{19}$$

Example 2. Effect of Pressure Difference on Capacity of a Rotary Vacuum Filter. A rotary vacuum filter with negligible filter-medium resistance delivers 100 cu ft of filtrate per hour when a given $CaCO_3$-H_2O mixture is filtered under known conditions. How many cubic feet of filtrate will be delivered per hour if the pressure drop over the cake is doubled, all other conditions remaining constant? Assume the $CaCO_3$ filter cake is noncompressible.

Solution

Equation (18) applies for this case:

$$100 = A_D\sqrt{\frac{2\psi_f N_R}{\alpha w\mu}}\sqrt{\Delta P_1} \tag{A}$$

$$\text{Unknown filtrate rate} = A_D\sqrt{\frac{2\psi_f N_R}{\alpha w\mu}}\sqrt{2\,\Delta P_1} \tag{B}$$

Dividing Eq. (*B*) by Eq. (*A*),

$$\text{Unknown filtrate rate} = 100\sqrt{2} = 141 \text{ cfh}$$

Air Suction Rate in Rotary Vacuum Filters. A vacuum pump must be supplied for the operation of a rotary vacuum filter, and the design engineer may need to estimate the size of pump and power requirement for a given filtration unit. Because air leakage into the vacuum system may supply a major amount of the air that passes through the pump, design methods for predicting air suction rates must be considered as approximate since they do not account for air leakage.

The rate at which air is sucked through the dewatering section of a rotary vacuum filter can be expressed in a form similar to Eq. (9) as

$$\frac{dV_a}{d\theta} = \frac{A_D\psi_a \, \Delta P}{(R'_F + R'_K)\mu_a} \tag{20}$$

where V_a = volume of air at temperature and pressure of surroundings sucked through cake in time θ

ψ_a = fraction of total surface available for air suction

μ_a = viscosity of air at temperature and pressure of surroundings

The cake resistance R'_K is directly proportional to the cake thickness l, and the filter-medium resistance R'_F can be assumed to be directly proportional to a fictitious cake thickness l'_F. Designating C'' as the proportionality constant,

$$R'_K + R'_F = C''(l + l'_F) \tag{21}$$

If the cake is noncompressible, l must be equal to the thickness of the cake leaving the filtering zone. Therefore, by Eq. (11) and using the same procedure as was followed in the development of Eq. (4),

$$l + l'_F = \frac{w(V_R + A_D\psi_a V'_F)}{\rho_c A_D} \tag{22}$$

where V'_F is the fictitious volume of filtrate per unit of air-suction area necessary to lay down a cake of thickness l'_F.

Combination of Eqs. (20) to (22) gives

$$\frac{dV_a}{d\theta} = \frac{A_D{}^2\psi_a \, \Delta P}{\beta w(V_R + A_D\psi_a V'_F)\mu_a} \tag{23}$$

where β equals C''/ρ_c and is known as the *specific air-suction cake resistance*.

Integration of Eq. (23) between the limits corresponding to $V_a = 0$ and $V_a = V_{aR}$, where V_{aR} designates the volume of air per revolution, gives

$$V_{aR} = \frac{A_D{}^2\psi_a \, \Delta P}{\beta w(V_R + A_D\psi_a V'_F)\mu_a N_R} \tag{24}$$

If the cake is compressible, a rough correction for variation in β with change in ΔP can be made by use of the following empirical equation:

$$\beta = \beta' \, (\Delta P)^{s'} \tag{24a}$$

where β' and s' are constants.

By neglecting the resistance of the filter medium, Eq. (24) can be simplified to

$$\text{Volume of air per revolution} = V_{aR} = \frac{A_D{}^2\psi_a \, \Delta P}{\beta w V_R \mu_a N_R} \tag{25}$$

$$\text{Volume of air per unit time} = V_{aR}N_R = \frac{A_D{}^2\psi_a\,\Delta P}{\beta w V_R \mu_a} \tag{26}$$

Equations (17), (19), and (26) can be combined to give

$$\text{Volume of air per unit time} = \frac{A_D\psi_a}{\beta\mu_a}\sqrt{\frac{\alpha\mu N_R\,\Delta P}{2w\psi_f}} \tag{27}$$

$$\frac{\text{Volume of air per unit time}}{\text{Weight of dry cake per unit time}} = \frac{\psi_a}{\psi_f}\,\frac{\mu}{\mu_a}\,\frac{\alpha}{2\beta w} \tag{28}$$

If the constants in the preceding equations are known for a given filter system and the assumption of no air leakage is adequate, the total amount of suction air can be estimated. This value, combined with a knowledge of the air temperature and the pressures at the intake and delivery sides of the vacuum pump can be used to estimate the power requirements of the vacuum pump by the methods described in Chap. 14.

Example 3. Estimation of Horsepower Motor Required for Vacuum Pump on a Rotary Vacuum Filter. A rotary vacuum-drum filter is to handle a slurry containing 20 lb of water per 1 lb of solid material. Tests on the unit at the conditions to be used for the filtration have shown that the dimensionless ratio of α/β is 0.6 and 19 lb of filtrate (not including wash water) is obtained for each 21 lb of slurry. The temperature of the surroundings and of the slurry is 70°F, and the pressure of the surroundings is 1 atm. The pressure drop to be maintained by the vacuum pump is 5 psi. The fraction of the drum area submerged in the slurry is 0.3, and the fraction of the drum area available for air suction is 0.1. On the basis of the following assumptions, estimate the horsepower of the motor necessary for the vacuum pump if the unit handles 50,000 lb of slurry per hour.

Assumptions:

Resistance of filter medium is negligible.

Any effects caused by air leakage are taken into account in the value given for α/β.

For air at the temperature involved, heat capacity at constant pressure divided by heat capacity at constant volume is 1.4.

The vacuum pump and motor have an over-all efficiency of 50 per cent based on an isentropic compression.

The value of β is based on the temperature and pressure of the air surrounding the filter.

The filter removes all of the solid from the slurry.

Solution

Because the value given for α/β applies at the operating conditions for the filtration and the resistance of the filter medium is negligible, Eq. (28) can be used:

$$\frac{\text{Volume of air per unit time}}{\text{Weight of dry cake per unit time}} = \frac{\psi_a}{\psi_f}\,\frac{\mu}{\mu_a}\,\frac{\alpha}{2\beta w}$$

$\psi_a = 0.1$
$\psi_f = 0.3$
μ = viscosity of water at 70°F = 0.982 centipoise = 0.982 × 2.42 lb/(hr)(ft)

μ_a = viscosity of air at 70°F = 0.018 centipoise = 0.018 × 2.42 lb/(hr)(ft)

$\dfrac{\alpha}{\beta} = 0.6$

Density of water at 70°F = 62.3 lb/cu ft

Pounds filtrate per pound of dry-cake solids = 19

$w = \dfrac{1}{19/62.3} = 3.28$ lb dry-cake solids/cu ft filtrate

Weight of dry cake/hr = $(50{,}000)(\frac{1}{21}) = 2380$ lb/hr

Volume of air/hr $= \dfrac{(2380)(0.1)(0.982 \times 2.42)(0.6)}{(0.3)(0.018 \times 2.42)(2 \times 3.28)} = 3960$ cfh at 70°F and 1 atm

By Eq. (26) in Chap. 14,

Theoretical horsepower for isentropic single-stage compression

$$= \frac{3.03 \times 10^{-5}k}{k-1} P_1 q_{fm_1} \left[\left(\frac{P_2}{P_1} \right)^{(k-1)/k} - 1 \right]$$

k = ratio of heat capacity of gas at constant pressure to heat capacity of gas at constant volume = 1.4

P_1 = vacuum-pump intake pressure = (14.7 − 5)(144) psf

P_2 = vacuum-pump delivery pressure = (14.7)(144) psf

q_{fm_1} = cubic feet of gas per minute at vacuum-pump intake conditions

$= \dfrac{(3960)(14.7)(144)}{(60)(14.7-5)(144)} = 100$ cfm at 70°C and 9.7 psia

Horsepower of motor required for vacuum pump

$$= \frac{(3.03 \times 10^{-5})(1.4)(14.7-5)(144)(100)}{(0.5)(1.4-1)} \left[\left(\frac{14.7}{9.7} \right)^{(1.4-1)/1.4} - 1 \right]$$

$$= 3.7 \text{ hp}$$

A 4-hp motor would be satisfactory.

COST DATA *

Information for making rough estimates of the cost for filters, centrifugal separators, mixers, and reactor tanks is presented in Figs. 17-6 through 17-10.

---

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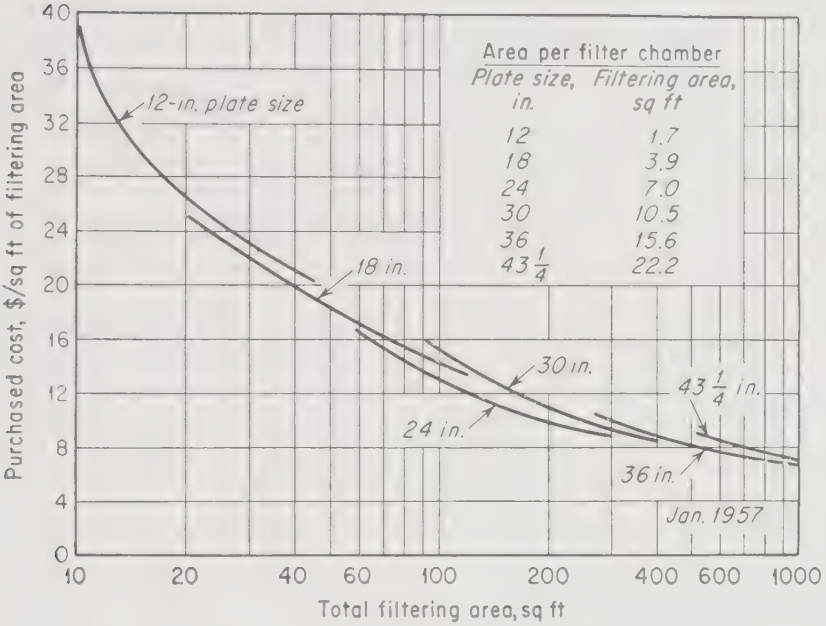

Area per filter chamber

Plate size, in.	Filtering area, sq ft
12	1.7
18	3.9
24	7.0
30	10.5
36	15.6
43 1/4	22.2

Multiplication factors
(*Based on cast-iron plate-and-frame filter presses*)

	Multipliers
Recessed-plate filter press	0.85
Material of construction:	
Aluminum	1.4
Bronze	2.3
Lead	2.8
Rubber-covered cast iron	3.5
Stainless (18-8) steel	6.0

FIG. 17-6. Cost of cast-iron plate-and-frame filter presses with 1-in. chambers.

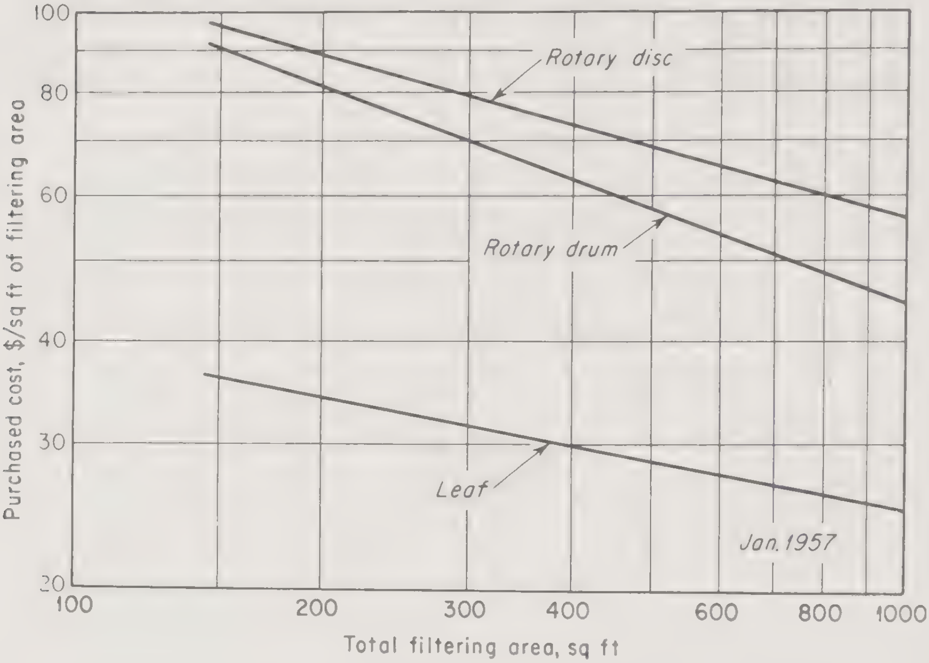

FIG. 17-7. Cost of vacuum filters (steel) not including auxiliaries.

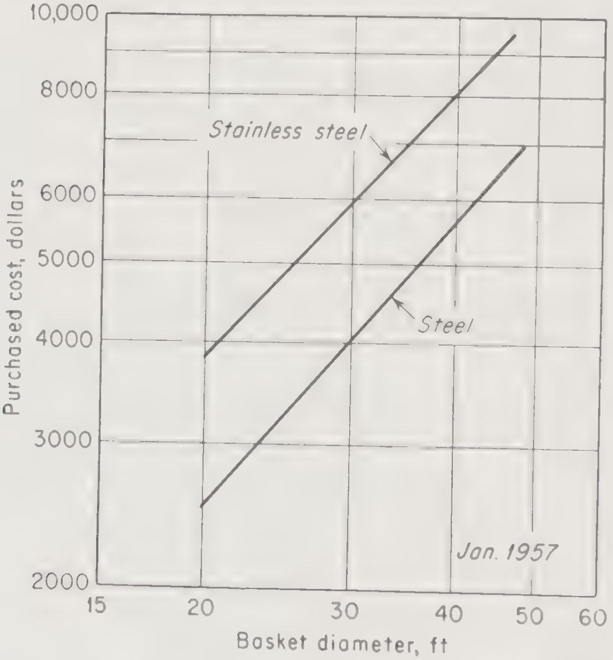

FIG. 17-8. Cost of top-suspended batch centrifugal separators.

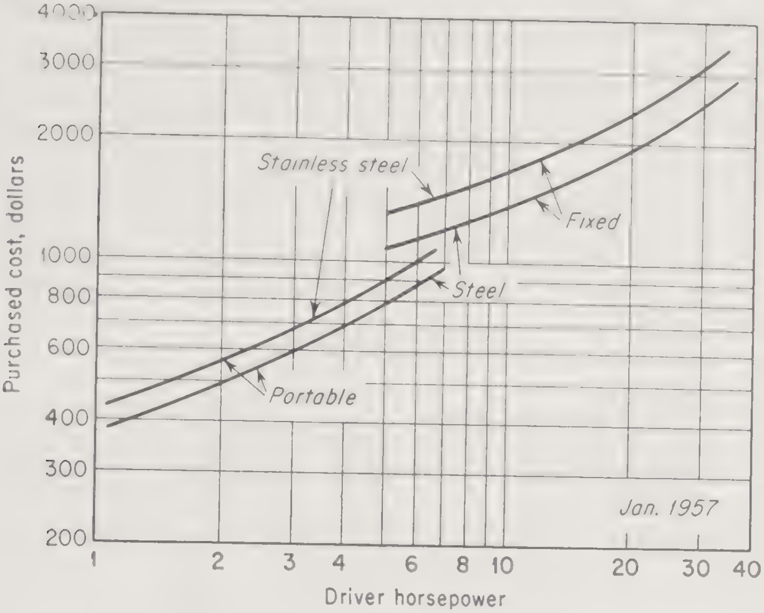

FIG. 17-9. Cost of propeller mixers.

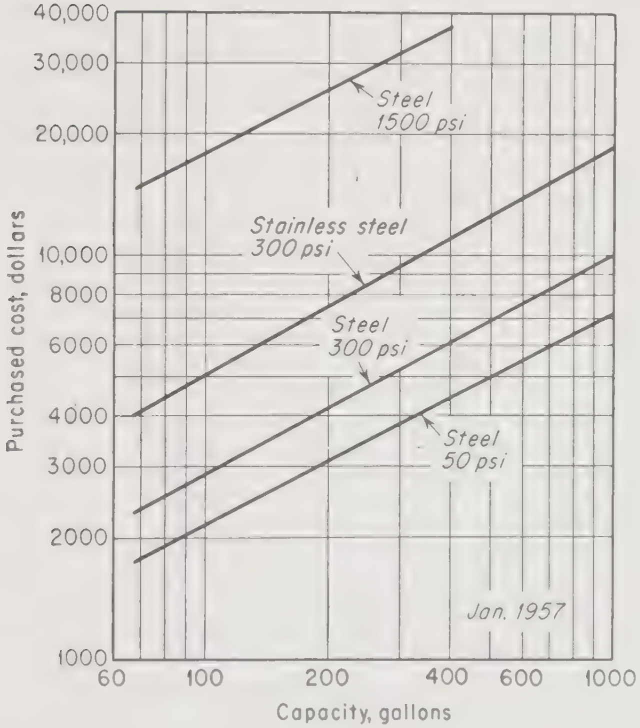

FIG. 17-10. Cost of agitated, jacketed reactor tanks.

NOMENCLATURE FOR CHAP. 17

A = area of filtering surface, sq ft
A_D = total available surface for filtration on continuous filter, sq ft
C' = a proportionality constant relating cake thickness to resistance to liquid passage
C'' = a proportionality constant relating cake thickness to resistance to air passage
k = ratio of heat capacity of gas at constant pressure to heat capacity of gas at constant volume
l = cake thickness at time θ, ft
l_F = fictitious cake thickness for liquid flow with resistance equal to that of filter medium, ft
l_F' = fictitious cake thickness for air flow with resistance equal to that of filter medium, ft
N_R = number of revolutions per unit time, revolutions/hr
P = total pressure; ΔP means pressure-difference driving force across filter; P_1 means vacuum-pump intake pressure; P_2 means vacuum-pump delivery pressure, psf
q_{fm_1} = cubic feet of gas flowing per minute at vacuum-pump intake conditions, cfm
R_F = resistance of filter medium to passage of liquid
R_F' = resistance of filter medium to passage of air
R_K = resistance of filter cake to passage of liquid
R_K' = resistance of filter cake to passage of air
s = compressibility exponent of filter cake, defined by Eq. (6)
s' = a constant, defined by Eq. (24a)
V = volume of filtrate delivered in time θ, cu ft
V_a = volume of air at temperature and pressure of surroundings sucked through filter cake in time θ, cu ft
V_{aR} = volume of air sucked through filter cake per revolution, cu ft/revolution
V_F = fictitious volume of filtrate per unit of filtering area necessary to lay down a cake of thickness l_F, cu ft/sq ft
V_F' = fictitious volume of filtrate per unit of air-suction area necessary to lay down a cake of thickness l_F', cu ft/sq ft
V_R = volume of filtrate delivered per revolution, cu ft/revolution
w = weight of dry-cake solids per unit volume of filtrate, lb/cu ft

Greek Symbols

α = alpha, specific cake resistance, hr^2/lb
α' = a constant, defined by Eq. (6)
β = beta, specific air-suction cake resistance, hr^2/lb
β' = a constant, defined by Eq. (24a)
Δ = delta, difference
θ = theta, time, hr
μ = mu, absolute viscosity of filtrate, lb/(hr)(ft)
μ_a = absolute viscosity of air at temperature and pressure of surroundings, lb/(hr)(ft)
ρ_c = rho, cake density as weight of dry-cake solids per unit volume of wet filter cake, lb/cu ft
ψ_a = psi, fraction of total surface area available for air suction
ψ_f = fraction of total available surface for filtration immersed in slurry

PROBLEMS

1. Filtration tests with a given slurry have indicated that the specific cake resistance α is 157 hr^2/lb. The fluid viscosity is 2.5 lb/(hr)(ft), and 3 lb of dry cake is formed per cubic foot of filtrate. The cake may be assumed to be noncompressible, and the resistance of the filter medium may be neglected. If the unit is operated at a constant pressure drop of 5 psi, what is the total filtering area required to deliver 30 cu ft of filtrate in ½ hr?

2. A rotary filter with a total filtering area of 8 sq ft has been found to deliver 10 cu ft of filtrate per minute when operating at the following conditions:

Fraction of filtering area submerged in the slurry = 0.2
rpm = 2
Pressure drop = 20 psi

Another rotary filter is to be designed to handle the same slurry mixture. This unit will deliver 100 cu ft of filtrate per minute and will operate at a pressure drop of 15 psi and a revolving speed of 1.5 rpm. If the fraction of filtering area submerged in the slurry is 0.2, estimate the total filtering area required for the new unit. In both cases, it may be assumed that no solids pass through the filter cloth, the cake is noncompressible, and the resistance of the filtering medium is negligible.

3. A plate-and-frame filter press is used to filter a known slurry mixture. At a constant pressure drop of 10 psi, 50 cu ft of filtrate is delivered in 10 min, starting with a clean filter. In a second run with the same slurry and filter press, 40 cu ft of filtrate is obtained in 9 min when the pressure drop is 6 psi, starting with a clean filter. What is the compressibility exponent for the cake if the resistance of the filter medium is negligible?

4. A slurry containing 1 lb of filterable solids per 10 lb of liquid is being filtered with a plate-and-frame filter press having a total filtering area of 250 sq ft. This unit delivers 10,000 lb of filtrate during the first 2 hr of filtration, starting with a clean unit and maintaining a constant pressure drop of 10 psi. The resistance of the filter medium is negligible. The time required for washing and dumping is 3 hr/cycle. The pressure drop cannot exceed 10 psi, and the unit is always operated at constant pressure drop.

The filter press is to be replaced by a rotary vacuum-drum filter with negligible filter-medium resistance. This rotary filter can deliver the filtrate at a rate of 1000 lb/hr when the drum speed is 0.3 rpm. Assuming the fraction submerged and the pressure drop are unchanged, what drum speed in rpm is necessary to make the amount of filtrate delivered in 24 hr from the rotary filter exactly equal to the maximum amount of filtrate obtainable per 24 hr from the plate-and-frame filter?

5. A plate-and-frame filter press with negligible filter-medium resistance is being used to filter a water slurry of constant composition. Experimental tests show that, during 3 hr of continuous operation, 300 cu ft of filtrate is delivered when the pressure drop is 20 psi and 150 cu ft of filtrate is delivered when the pressure drop is 5 psi. The unit is to be operated at a constant pressure drop of 15 psi during filtration and washing. The cake will be washed with 10 cu ft of water at the end of 2 hr of continuous filtration. If reverse thorough washing (i.e., wash rate = ¼ of final filtrate delivery rate) is used, estimate the time required for washing.

6. A slurry is filtered, and the filter cake is washed by use of a plate-and-frame filter press operated at a constant pressure drop of 40 psi throughout the entire run. Experimental tests have been carried out on this equipment, and the results for the slurry mixture used can be expressed as follows for any one pressure drop:

$$\theta \, \Delta P = k' \left(\frac{V}{A}\right)^2 + k'' \frac{V}{A}$$

where k' and k'' are constants. At a pressure drop of 40 psi, 0.02 lb of filtrate is collected in 1.8 min for each square inch of cloth area, and 0.08 lb of filtrate per square inch of cloth area is collected in 22.2 min. Calculate the time required to filter and wash the cake formed when 0.11 lb of filtrate has been collected per square inch of cloth area if an amount of wash water equal to half the filtrate is used. The specific gravities of the filtrate and wash water are 1.0, and both are at the same temperature. Simple forward washing is used so that the washing rate is equal to the filtrate delivery rate at the end of the filtration.

7. The design of a cast-iron plate-and-frame filter press has indicated that a unit with a total filtering area of 100 sq ft and 1-in. chambers is needed. On the basis of the information presented in Fig. 17-6, estimate the number of chambers in the press with the minimum purchased cost.

APPENDIX A

DESIGN PROBLEMS

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MAJOR PROBLEMS *

PROBLEM 1. PLANT FOR SOLVENT RENDERING OF RAW TISSUES

MEMORANDUM
TO: Assistant Design Engineer
FROM: A. B. White, Head
Process Development Division

You are to prepare a complete preliminary-estimate design for a new plant for the solvent rendering of raw tissues by an extraction process. Some pieces of equipment are now on hand which we believe can be used in the new plant. Please submit a complete report on the design which you feel will be most favorable for our company. We are particularly interested in total investment, yearly profit before taxes, and the probable per cent return on the investment. We shall be interested in the reason for your particular choice of solvent. The design report should also include the number of operators necessary and the approximate operating procedure.

We are considering expansion of our present plant to include an extraction process for treating 50 tons of raw fish per day. The average analysis of the fish as received by our plant is as follows:

	% by weight
Water	70
Soluble oils	10
Insolubles	20

The general process has been described in some detail in the literature and in patents (see references at end of problem); however, our proposed method is presented roughly in the following:

The General Process

The process is to be carried out at a sufficiently low temperature for the biological substances to remain essentially unchanged, except for the removal of oil and water. The top temperature limit for the insoluble materials and the oils is 90°C.

The raw fish as received are ground and delivered to a slurry tank where the pulped material is agitated. The slurry is then sent to cookers where the oil is extracted by a suitable solvent and the water is evaporated along with the solvent. The evolved vapors are condensed, and the solvent and the water are separated by decanting.

The liquid-and-solid mixture from the batch cookers is filtered, and the solid is desolventized to give a fish-meal product.

The filtrate, containing solvent and dissolved fish oil, is sent to a steam-jacketed kettle where the oil is recovered by distilling off the solvent. The oils are finally passed through a steam stripper where the final traces of solvent are removed and the oil is deodorized. The fish-oil product is obtained from the bottom of the steam stripper

A general flow diagram is included with this problem (Fig. A-1), but this diagram does not show any of the details.

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* Time period of 30 days recommended for individual student solution.

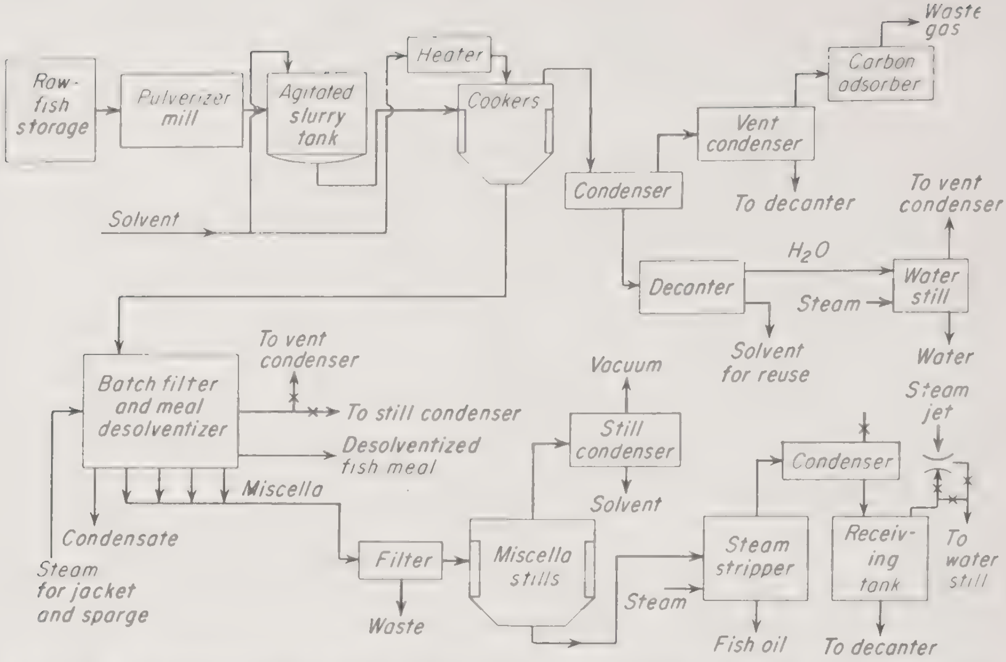

FIG. A-1. Suggested rough flow diagram showing extraction process for fish-oil recovery. (Details are not included, and changes may be necessary.)

Solvents. The following solvents should be considered for possible use: trichloroethylene, ethylene dichloride, perchloroethylene, and carbon tetrachloride. The solvents may be purchased in tank-car lots since storage space is available.

Special Conditions. To ensure adequate water removal, the cooker must be operated for ½ hr at the boiling temperature of the pure solvent.

The final dry fish meal may not contain more than 1 per cent oil by weight.

The weight ratio of solvent to insolubles at the end of each cooker batch must be 3:1. The fish-meal filter cake must be washed with a weight of solvent at least equal to the weight of the dry fish meal in order to ensure adequate oil removal.

The mixture in the slurry tank contains 50 wt % solvent and 50 wt % fish.

Cooling water is available at 15°C.

The solid material remaining after filtration contains 1.0 lb of solvent per pound of dry fish meal.

Tanks larger than 9 ft in diameter or 11 ft high cannot be used under the plant conditions.

The steam pressure in the plant is 30 psig.

Superheated solvent vapor may be used to provide additional heat for the cooker.

Assumptions and Data. The effective molecular weight of the oil may be assumed to be 150. The vapor pressure of the oil is negligible under the conditions of the process.

Heat capacities and specific volumes for individual components making up the mixtures may be considered as additive. The following values apply between 20 and 100°C:

c_p of insolubles = 0.2 Btu/(lb)(°F)
c_p of oil = 0.3 Btu/(lb)(°F)
sp gr of oil = 0.7
Equivalent sp gr of insolubles = 0.8

The only source of solvent loss is from the waste water discarded from the water still.

The liquid leaving all condensers is 5°C below the boiling point.

The temperature of the slurry entering the cookers is 25°C.

The temperature of the liquid entering the Miscella stills is 30°C.

The liquid enters the steam stripper at the same temperature it had leaving the Miscella still.

The desolventized fish meal contains no solvent.

The total fixed-capital investment for the installed equipment may be obtained by multiplying the cost of all the primary and accessory equipment by 4. This factor takes care of construction costs and all other fixed costs such as piping, valves, instrumentation, new buildings, etc. (This, of course, does not include the original solvent cost or any raw materials.)

Over-all heat-transfer coefficient in all condensers = 150 Btu/(hr)(sq ft)(°F).

Over-all heat-transfer coefficient in cookers and in Miscella stills = 100 Btu/(hr)(sq ft)(°F) (applies for walls or tubes).

Coils may not be used in the cookers.

The liquid leaving the Miscella still may be assumed to contain 8 per cent solvent by weight.

The steam stripper is steam-jacketed, and the oil must leave the bottom at a temperature less than 100°C. In order to ensure complete removal of the solvent from the oil and to deodorize the oil, use excess steam amounting to 30 per cent of the weight of the oil.

No agitators are necessary in the cookers or Miscella tanks, because the boiling supplies sufficient agitation.

The total amount of steam theoretically necessary for the process should be increased by 20 per cent to take care of unaccounted-for heat losses.

The plant operates 300 days per year.

Equipment. The following equipment is now available at the plant:

Fish-pulverizing mill
All necessary storage tanks and receiving tanks
The slurry tank complete with agitator
Batch filter and meal desolventizer
Decanter still
Water still
Vacuum ejectors (valued at $1000)
Waste filter
Steam stripper
Vent condenser and carbon adsorber

These pieces of equipment are not installed. Preliminary estimates have indicated that all of these pieces of equipment have adequate capacity for the present design. They are valued at a total of $60,000. For the purpose of your cost estimates, you may assume the $60,000 will cover the cost of the listed equipment. *However*, your design should include complete specifications for *all* the equipment necessary for the new plant. In this way, we will be able to have a final check to show us if the present equipment on hand is satisfactory.

It will be necessary to purchase the cookers, the Miscella stills, the condensers and the heaters for these pieces of equipment, and all pumps.

Costs. The necessary working-capital investment which must be kept on hand for the new plant is estimated to be $30,000.

Annual fixed charges = 25 per cent of total investment.

Annual direct production costs for this process (with the exception of raw material and steam costs) plus costs for plant overhead, administration, office help, distribution, and contingencies are $100,000 per year. This $100,000 includes the cost of operating any vacuum equipment and is unchanged even if vacuum is not used in the process.

Tanks. Suitable for cookers or Miscella stills (diameter less than 9 ft):

Material	Cost for one 1000-gal tank	
	Without steam jacket	With steam jacket
Carbon steel.........	$1100	$2000
Stainless steel........	3000	4200

The tanks are available in standard sizes of (in gallons) 100, 200, 300, 500, 750, 1000, 1500, 2000, 5000, 10,000.

Assume that the cost of each standard tank varies as $(\text{volume})^{2/3}$.

If heating coils are to be inserted in a tank, increase the cost of the tank by 10 per cent and by 10 times the cost of the pipe or tubing making up the coil. (This is an approximation to take care of extra costs for fabrication, special materials, etc. It applies only to a reasonable length of coil.)

Heat Exchangers. Shell-and-tube type (for condensers and heaters):

Material	Dollars per sq ft of tube surface (pressures from 25 psig to 0 in. Hg)					
	Square feet					
	50	100	200	300	500	1000
Carbon steel...............	17	13	10	8	6	5
Stainless steel..............	35	28	21	17	14	11

Steam Cost. $0.50/1000 lb.

Materials

Cost of raw fish (delivered at plant) = $32.00/ton
Selling price for fish meal of plant-product grade = $0.08/lb
Selling price for fish oil of plant-product grade = $0.13/lb

References

1. E. Levin and R. K. Finn, A Process for Dehydrating and Defatting Tissues at Low Temperature, *Chem. Eng. Progr.*, **51**:233 (1955).

2. E. Levin and F. Lerman, An Azeotropic Extraction Process for Complete Solvent Rendering of Raw Tissues, *J. Am. Oil Chem. Soc.*, **28**:441 (1951).
3. E. M. Worsham and E. Levin, Simultaneous Defatting and Dehydrating of Fatty Substances, U.S. Patent No. 2,503,312 (Apr. 11, 1950).
4. E. Levin, Production of Dried, Defatted Enzymatic Material, U.S. Patent No. 2,503,313 (Apr. 11, 1950).
5. E. Levin, Drying and Defatting Tissues, U.S. Patent No. 2,619,425 (Nov. 25, 1952).
6. Defatting Distillery, *Ind. Eng. Chem.*, **42**:14A (June, 1950).
7. E. W. McGovern, Chlorohydrocarbon Solvents, *Ind. Eng. Chem.*, **35**:1230 (1943).

PROBLEM 2. PENTAERYTHRITOL PLANT

You are a design engineer with the ABC Chemical Company, located at Wilmington, Del. Mr. Charles B. King, Supervisor of the Process Development Division, has asked you to prepare a preliminary design of a new plant that will produce pentaerythritol.

The following memo has been given to you by Mr. King:

Dear Sir:

We are considering construction of a pentaerythritol plant at Louisiana, Missouri. At the present time, we have an anhydrous ammonia plant located at Louisiana, Missouri, and we own sufficient land at this site to permit a large expansion.

As yet, we have not decided on the final plant capacity, but we are now considering construction of a small plant with a capacity of 60 tons of technical grade pentaerythritol per month. Any work you do on the design of this plant should be based on this capacity.

Sufficient water, power, and steam facilities for the new plant are now available at the proposed plant site. Some stand-by equipment is located at our existing plant in Louisiana, and we may be able to use some of this in the pentaerythritol plant. However, you are to assume that all equipment must be purchased new.

Please prepare a preliminary design for the proposed plant. This design will be surveyed by the Process Development Division and used as a basis for further decisions on the proposed plant. Make your report as complete as possible, including a detailed description of your recommended process, specifications and cost estimates for the different pieces of equipment, total capital investment, and estimated return on the investment assuming we can sell all our product at the prevailing market price. We shall also be interested in receiving an outline of the type and amount of labor required, the operating procedure, and analytical procedures necessary.

Present what you consider to be the best design. Although our legal department will conduct a patent survey to determine if any infringements are involved, it would be helpful if you would indicate it if you know that any part of your design might involve patent infringements.

Enclosed you will find information on our utilities situation, amortization policy, labor standards, and other data.

C. B. King, Supervisor
Process Development Division

Enclosure: Information for Use in Design of Proposed Pentaerythritol Plant

Utilities. Water—available for pumping at 65°F; cost, \$0.05 per 1000 gal. Steam—available at 100 psig; cost, \$0.50 per 1000 lb. Electricity—cost, \$0.01 per kwhr.

Storage. No extra storage space is now available.

Transportation Facilities. A railroad spur is now available at the plant site.

Labor. Chief operators, \$2.20 per hour; all helpers and other labor, \$1.40 per hour.

Amortization. Amortize in 10 years.

Return on Investment. For design calculations, we require at least a 20 per cent return before income taxes on any unnecessary investment.

Income Taxes. The income-tax load for our company amounts to 46 per cent of all profits.

Raw-materials Costs. All raw materials must be purchased at prevailing market prices.

Heats of Reaction. With sodium hydroxide as the catalyst, 64,000 Btu is released per pound mole of acetaldehyde reacted. With calcium hydroxide as the catalyst, 60,000 Btu is released per pound mole of acetaldehyde reacted.

Heat-transfer Coefficients. Steam to reactor liquid, 200 Btu/(hr)(sq ft)(°F). Water to reactor liquid, 150 Btu/(hr)(sq ft)(°F).

Suggested References. Organic and process-industries books such as W. L. Faith, D. B. Keyes, and R. L. Clark, "Industrial Chemicals," John Wiley & Sons, Inc., New York, 1950; W. D. Morrison, *Chem. Eng. News*, **31**:659 (1953); M. S. Peters and J. A. Quinn, *Ind. Eng. Chem.*, **47**:1710 (1955); U.S. Patents and Industrial Bulletins.

PROBLEM 3. FORMALDEHYDE PLANT

Illinois Chemical Process Corporation
Plant Development Division
Urbana, Illinois

Gentlemen:

We are considering entering the field of production of formaldehyde, and we should like to have you submit a complete preliminary design for a 70-ton-per-day formaldehyde plant (based on 37 wt % formaldehyde) to us.

We have adequate land available for the construction of the plant at Centralia, Illinois, and sufficient water and steam are available for a plant of the desired capacity. Please make your report as complete as possible, including a detailed description of your recommended process, specifications and cost estimates for the different pieces of equipment, total capital investment, and estimated return on the investment assuming we can sell all our production at the prevailing market price. We shall also be interested in receiving an outline of the amount and type of labor required, the operating procedure, and analytical procedures necessary.

Enclosed you will find information concerning our utilities situation, amortization policy, labor standards, product specification, etc.

Very truly yours,

A. B. Blank
Technical Superintendent
Centralia Chemical Company
Centralia, Illinois

ABB:jf
Enclosure

Enclosure

Utilities. Water—available for pumping at 70°F; cost, $0.05 per 1000 gal. Steam—available at 200 psig; cost, $0.40 per 1000 lb. Electricity—cost, $0.01 per kwhr.

Storage. No extra storage space is now available.

Transportation Facilities. A railroad spur is now available at the plant site.

Land. The plant site is on land we own which is now of no use to us. Therefore, do not include the cost of the land in your analysis.

Labor. Chief operators, $1.90 per hour; all helpers and other labor, $1.40 per hour.

Amortization. Amortize in 10 years.

Return on Investment. For design comparison, we require at least a 15 per cent return per year on any unnecessary investment.

Product Specification. All formaldehyde will be sold as N.F. solution containing 37.0 wt % formaldehyde and 8 wt % methanol. All sales may be considered to be by tank car.

Suggested References. J. F. Walker, "Formaldehyde," 2d ed., Reinhold Publishing Corporation, New York, 1953; R. N. Hader, R. D. Wallace, and R. W. McKinney, Formaldehyde from Methanol, *Ind. Eng. Chem.*, **44**:1508 (1952); T. R. Olive, Durez Synthesizes Formaldehyde, *Chem. Eng.*, **56**(2):130, 146 (1949); Quarterly Chemical Price Report, *Chem. Eng. News.*

MINOR PROBLEMS *

PROBLEM 1. OPTIMUM TEMPERATURE FOR SULFUR DIOXIDE REACTOR

The head of your design group has asked you to prepare a report dealing with the use of a special catalyst for oxidizing SO_2 to SO_3. This catalyst has shown excellent activity at low temperatures, and it is possible that it may permit you to get good SO_3 yields by using only one standard-size reactor instead of the conventional two.

Your report will be circulated among the other members of your design group and will be discussed at the group meetings. This report is to be submitted to the head of your design group.

Some general remarks concerning your report follow:

A. The report should include the following:
  1. Letter of transmittal (the letter to the head of your group telling him you are submitting the report and giving any essential results if applicable)
  2. Title page
  3. Table of contents
  4. Summary (a concise presentation of the results)
  5. Body of report
     - *a*. Introduction (a brief discussion to explain what the report is about and reason for the report; no results should be included here)
     - *b*. Discussion (outline of method of attack on the problem; do not include any detailed calculations; this should bring out technical matters not important enough to be included in the Summary; indicate assumptions and reasons; include any literature survey results of importance; indicate possible sources of error, etc.)
     - *c*. Final recommended conditions (or design if applicable) with appropriate data (a drawing is not necessary in this case although one could be included if desired)
  6. Appendix
     - *a*. Sample calculations (clearly presented and explained)
     - *b*. Table of nomenclature (if necessary)
     - *c*. Bibliography (if necessary)
     - *d*. Data employed

B. The outline as presented above can be changed if desired (for example, a section on conclusions and recommendations might be included)

C. The report can be made more effective by appropriate subheadings under the major divisions

The Problem

A new reactor has recently been purchased as a part of a contact sulfuric acid unit. This reactor is used for oxidizing SO_2 to SO_3 employing a vanadium oxide catalyst.

Using the following information and data, determine the temperature at which the reactor should be operated to give the maximum conversion of SO_2 to SO_3, and indicate the value (as per cent) of this maximum conversion. Ten thousand pounds of SO_2 enters the reactor per day.

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* Time period of 14 days recommended for individual student solution.

Air is used for the SO_2 oxidation, and it has been decided to use 300 per cent excess air. Preheaters will permit the air and SO_2 to be heated to any desired temperature, and cooling coils in the reactor will maintain a constant temperature in the reactor. The reactor temperature and the entering air-and-SO_2 temperature will be the same. The operating pressure may be assumed to be 1 atm.

The inside dimensions of the reactor are 5 by 5 by 8 ft. One-half of the inside reactor volume is occupied by the catalyst.

Your laboratory has tested a special type of vanadium oxide catalyst, and, on their recommendation, you have decided to use it in the reactor. This catalyst has a void fraction of 60 per cent (i.e., free space in catalyst/total volume of catalyst = 0.6).

The reaction $2SO_2 + O_2 \rightarrow 2SO_3$ proceeds at a negligible rate except in the presence of a catalyst.

Your laboratory has run careful tests on the catalyst. The results indicate that the reaction is not third-order but is a complex function of the concentrations. Your laboratory reports that the reaction rate is proportional to the SO_2 concentration, inversely proportional to the square root of the SO_3 concentration, and independent of the oxygen concentration.[*][†]

This may be expressed as

$$\frac{dx}{dt} = k\frac{a - x}{x^{1/2}}$$

where a = SO_2 originally present as pound, lb mole/cu ft
x = number of pounds mole of SO_2 converted in t sec of catalyst contact time per cubic foot of initial gas
k = specific reaction-rate constant, (lb mole/cu ft)$^{1/2}$/sec; this may be assumed to be constant at each temperature up to equilibrium conditions

The laboratory has obtained the data given in Table 1 for the reaction-rate constant. These data are applicable to your catalyst and your type of reactor.

Table 1

$k \times 10^4$, *(lb mole/cu ft)*$^{1/2}$*/sec* *	*Temperature, °C*
14	350
30	400
60	450
100	500
210	550

* Applicable only to the conditions of this problem.

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[*] A. M. Fairlie, "Sulfuric Acid Manufacture," Reinhold Publishing Corporation, p. 331 (Platinum Catalyst), New York, 1936.

[†] Modern tests indicate that this may not be the case with some vanadium oxide reactors. T. Baron (Ph.D. thesis, University of Illinois, 1948) reports that the rate is proportional to the SO_2 concentration and inversely proportional to the square root of the O_2 concentration. However, you use your laboratory data.

The data of standard-state free-energy values at different temperatures given in Table 2 were obtained from the literature. These data apply to the reaction

$$SO_2 + \frac{1}{2}O_2 \rightleftharpoons SO_3$$

TABLE 2

ΔF^0, *cal/g mole*	*Temperature, °C*
−9120	350
−8000	400
−7000	450
−5900	500
−4900	550

The fugacities of the gases involved may be assumed to be equal to the partial pressures.

PROBLEM 2. HEAT-EXCHANGER DESIGN

TO: Assistant Process Engineer
FROM: Dr. A. B. Green, Chief Design Engineer
Illco Chemical Company
Clarksdale, Illinois

We are in the process of designing a catalytic cracker for our petroleum division. As part of this work, will you please submit a design for a single-pass heat exchanger based on the information given below?

It is estimated that 200,000 gph of oil *A* must be heated from 100 to 230°F. The heating agent will be saturated steam at 50 psig.

The engineering department has indicated that the exchanger will cost $5.00 per square foot of inside heating area. This cost includes all installation.

You can neglect any resistance due to the tube walls or steam film; so all the heat-flow resistance will be in the oil film.

The cost of power is 3 cents per kilowatthour, and the efficiency of the pump and motor installation is estimated to be 60 per cent.

Do not consider the cost of steam or exchanger insulation in your analysis.

The oil will flow inside the tubes in the heat exchanger. Following are data on oil *A* which have been obtained from the Critical Tables and the Chemical Engineers' Handbook:

Avg viscosity of oil *A* between 100 and 230°F = 6 centistokes
Avg density of oil *A* between 100 and 230°F = 0.85 g/cu cm
Avg sp ht of oil *A* between 100 and 230°F = 0.48
Avg thermal conductivity of oil *A* between 100 and 230°F = 0.08 Btu/(hr)(sq ft)(°F/ft)

We recommend that the Reynolds number be kept above 5000 in this type of exchanger.

The tubes in the exchanger will be made from standard steel tubing. Tube sizes are available in ½-in.-diameter steps. Tubing wall is 16 BWG.

We are particularly interested in the diameter of the tubes we should use, the length of the tubes, and the total cost of the installed unit. In case the exchanger length is unreasonable for one unit, what would you recommend?

Assume the unit will operate continuously for 300 days each year. Fixed charges are 16 per cent.

Remember that our company demands a 20 per cent return on all extra fixed-capital investments.

You may base your calculations on a total of 100 tubes in the exchanger.

Please submit this information as a complete formal report. Include a short section outlining what further calculations would have been necessary if the specification of 100 tubes in a one-pass exchanger had not been given.

Following are recommended assumptions:

You may assume that the Fanning friction factor can be represented by

$$f = \frac{0.04}{(N_{\mathrm{Re}})^{0.16}}$$

You may assume that the oil-film heat-transfer coefficient is constant over the entire length of the exchanger.

For simplification, assume that the oil-film heat-transfer coefficient may be represented by (standard heat-transfer nomenclature)

$$h = 0.023 \frac{k}{D} (N_{\mathrm{Re}})^{0.8}(N_{\mathrm{Pr}})^{0.4}$$

where all variable values are at the average value between 100 and 230°F.

PROBLEM 3. DESIGN OF SULFUR DIOXIDE ABSORBER

You are a member of a group of design engineers designing equipment for the recovery of SO_2 from stack gases.

The group leader has asked you to determine the optimum size of the SO_2 absorption tower. Specifically, he has asked you to determine the height and cross-sectional area of the optimum absorption tower and to present your recommendations in the form of a formal report.

Your group has held several meetings to discuss the proposed over-all design. Following is a list of conditions, assumptions, and data on which the group has decided to base the design:

100,000 cu ft of gas per minute at 300°F and 1 atm are to be treated.
The entering gas contains 0.3 per cent by volume SO_2 and 11.0 per cent CO_2, with the balance being N_2, O_2, and H_2O.
The average molecular weight of the entering gas = 29.4.
The mole per cent SO_2 in the exit gas is to be 0.01 per cent.
The entering and exit pressures of the absorption column may be assumed to be 1 atm for purposes of calculating the SO_2 pressures.

The zinc oxide process will be used for recovering the SO_2. In this process, a solution of H_2O, $NaHSO_3$, and Na_2SO_3 is circulated through the absorption tower to absorb the SO_2. This mixture is then treated with ZnO, and the $ZnSO_3$ formed is filtered off, dried, and calcined to yield practically pure SO_2. The ZnO from the calciner is reused, and the sulfite-bisulfite liquor from the filter is recycled.

The absorption tower will contain nonstaggered wood grids of the following dimensions:

Clearance = 1.5 in.
Height = 4 in.
Thickness = ¼ in.
Free cross-sectional area = 85.8%
Active absorption area per cubic foot of volume = a = 13.7 sq ft/cu ft

The average density of the gas at the tower entrance can be assumed to be 0.054 lb/cu ft. The sulfite-bisulfite liquid has a density of 70 lb/cu ft and can be considered as having a zero equilibrium SO_2 vapor pressure at both the inlet and outlet of the tower).

The sulfite-bisulfite liquid must be supplied at a rate of 675 lb/(hr)(sq ft of column cross-sectional area).

The optimum design can be assumed to be that corresponding to a minimum total power cost for circulating the liquid and forcing the gas through the tower. You may assume that this optimum corresponds to the optimum that would be obtained if fixed charges were also considered.

The following simplified equations are applicable for grids of the dimensions to be used:

$$K_g = 0.00222(G_0)^{0.8}$$

$$\frac{\Delta h_w}{L} = 0.23 \times 10^{-7}(G_0)^{1.8}$$

where K_g = molar absorption coefficient, lb mole of component absorbed/(hr)(sq ft)(atm)$_{\text{log mean}}$
G_0 = superficial mass velocity of gas in tower, lb/(hr)(sq ft)
Δh_w = pressure drop through tower, in. of water
L = height of tower, ft

The liquid is put into the absorption tower by means of a nozzle at the top of the tower. The pressure just before the nozzle is 35 psig. Assume the pump for the liquid must supply power to lift the liquid to the top of the tower and compress the liquid to 35 psig. Use a 10 per cent safety factor on the above pumping-power requirements to take care of the friction in the lines and other minor losses.

The gas blower has an over-all efficiency of 55 per cent.

The pump has an over-all efficiency of 65 per cent.

Reference. H. F. Johnstone and A. Singh, *Ind. Eng. Chem.*, **29**:286 (1937).

PRACTICE-SESSION PROBLEMS *

PROBLEM 1. COST FOR HYDROGEN RECOVERY BY ACTIVATED-CHARCOAL ADSORPTION PROCESS

What is the cost, as cents per 1000 cu ft (at SC) of 95 mole % H_2, for recovering hydrogen of 95 mole % purity from 10 million cu ft (at SC) of gaseous feed per day if the following conditions apply?

Feed composition by volume = 72.5 per cent H_2 and 27.5 per cent CH_4.

A hydrogen-recovery method based on selective adsorption by activated charcoal will be used.

For the charcoal adsorption, three separate beds will be needed so that one bed can be in continuous use while the other two are being desorbed or reactivated. Base the recovery on a single pass and an adsorption cycle of 1 hr per bed.

0.00838 mole of material is adsorbed per hour per pound of activated charcoal.

The composition of the adsorbed phase is 96.8 mole % CH_4, the balance being hydrogen.

The cost of activated charcoal is $0.75 per pound.

The annual amount of additional charcoal necessary is 15 per cent of the initial charge.

The total plant cost (equipment, piping, instrumentation, etc.) equals $977,000.

The capital investment equals the total plant cost plus process materials (process materials are considered as auxiliaries—i.e., process materials are only the initial charge of activated charcoal).

The capital investment must be completely paid off (no scrap value) in 5 years.

The operating cost per year, including labor, fuel, water, feed, regeneration, fixed charges minus depreciation, and repairs and maintenance, equals $463,000 (only operating costs not included here are the cost of the additional make-up charcoal necessary and depreciation).

The plant operates 350 days/year.

Reference. AIChE Student Contest Problem, 1947.

PROBLEM 2. ADSORPTION-TOWER DESIGN FOR HYDROGEN PURIFICATION BY ACTIVATED CHARCOAL

Your plant is producing 10 million cu ft (measured at SC) per day of a gas containing 72.5 vol % H_2 and 27.5 vol % CH_4. It is proposed to pass this gas through activated charcoal to obtain a product gas containing 95 vol % H_2. The activated charcoal shows a preferential selective adsorption of the CH_4.

An adsorption-desorption-regeneration cycle using three fixed beds will be used. One bed will be regenerated and purged over an 8-hr period. During this period, the other two beds will be on alternate 1-hr adsorption and 1-hr desorption cycles to permit a continuous operation. A single pass of the gas will be used.

Each individual bed may be designed to include a number of charcoal-packed towers in parallel. The diameter of the individual towers must all be the same, and the diameter may be 6, 9, 12, or 15 ft.

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* The following problems are recommended for solution by students working in groups of two or three during a 3-hr practice session.

Determine the following:

(*a*) The number of individual units (or towers) in each bed to give the minimum total cost for the towers.

(*b*) The height and diameter of the towers for the conditions in part *a*.

Data and information previously obtained for the chosen conditions of the process (i.e., adsorption at 400 psia, desorption at 20 psia, and an average adsorption temperature of 110°F) *are as follows:*

0.0063 lb mole of material is adsorbed per hour per pound of activated charcoal.
The composition of the adsorbed phase is 96.8 mole % CH_4, the balance being H_2.
The charcoal has a bulk density of 0.30 g/cu cm.

The gas velocity in the adsorbers should not exceed 1 fps based on the cross-sectional area of the empty vessel. This applies to all the cycles including the adsorption and the regeneration and purge.

The feed gases enter the adsorbers at 400 psia and 80°F. The product gases leave the adsorbers at almost 400 psia and a temperature of 140°F. Regeneration includes 30 cu ft (SC) of flue gas per pound of charcoal and 80 standard cubic feet of purging air per pound of charcoal. The flue gas is at 600°F (its maximum temperature) and 5 psig, and the air is at 90°F and 5 psig. The air may reach a maximum temperature of 600°F at the start of the purging.

TABLE 3. COST DATA

Column diameter, ft..........	6	9	12	15
Dollars per foot of length.....	360	660	1010	1800
Cost per tower for skirt or support, dollars...............	600	1000	1400	1600

For each head (either top or bottom), add equivalent cost of 5 ft additional length per vessel.

Reference. AIChE Student Contest Problem, 1947.

PROBLEM 3. DESIGN OF ROTARY FILTER FOR SULFUR DIOXIDE RECOVERY SYSTEM

As a member of a design group working on the design of a recovery system for SO_2, you have been asked to estimate the area necessary for a rotary vacuum filter to handle a zinc sulfite filtration. You are also to determine the horsepower of the motor necessary for the vacuum pump. Do not include any safety factors in your results.

The following conditions have been set by your group:

A slurry containing 20 lb of liquid per pound of dry $ZnSO_3 \cdot 2.5H_2O$ is to be filtered on a continuous rotary filter to give a cake containing 0.20 lb of H_2O per pound of dry hydrate.

One hundred pounds of $ZnSO_3 \cdot 2.5H_2O$ in the slurry mixture will be delivered to the filter per minute.

A drum speed of 0.33 rpm will be used, and a vacuum of 10.2 in. mercury below atmospheric pressure will be used.

The fraction of drum area submerged will be assumed to be 0.25.

The fraction of drum area available for air suction will be assumed to be 0.10.

The temperature of the slurry is 110°F, and the air into the vacuum pump can be considered to be at 110°F. C_p/C_v for air at 110°F = 1.4. The temperature and pressure of the air surrounding the filter are 70°F and 1 atm, respectively.

The specific cake resistance and the specific air-suction cake resistance can be assumed to be independent of pressure drop, drum speed, temperature, fraction of drum submerged, fraction of drum available for suction, and slurry concentration. However to eliminate possible errors due to this assumption, a lab test should be run at conditions approximating the planned design. The results of these tests can be used as a basis for the design (i.e., cake and filtrate compositions and densities can be assumed to be the same for the design as those found in the lab).

The vacuum pump and motor have an efficiency (isentropic) of 85 per cent.

It can be assumed that all of the $ZnSO_3 \cdot 2.5H_2O$ is filtered off and none remains in the filtrate.

The resistance of the filter medium can be assumed to be negligible.

Laboratory data compiled at the request of SO_2-recovery design group (results of filtration of zinc sulfite slurry on Oliver rotary vacuum filter) are as follows:

Total area of filter	4.15 sq ft
Fraction of area submerged	0.20
Fraction of area available for air suction	0.10
Vacuum	9 in. Hg below atmospheric pressure
Slurry concentration	12 lb liquid/lb dry $ZnSO_3 \cdot 2.5H_2O$
Temperature	110°F
Drum speed	0.40 rpm
Density of wet cake leaving filtering zone	100 lb/cu ft
Pounds of liquid per pound of dry $ZnSO_3 \cdot 2.5H_2O$ in wet cake leaving filtering zone	0.6
Density of filtrate	68.8 lb/cu ft
Viscosity of filtrate	0.6 centipoise
Pounds of water per pound of dry $ZnSO_3 \cdot 2.5H_2O$ in final cake	0.20
Time interval	5.0 min
Volume of filtrate	0.95 cu ft
Volume of air at SC	8.5 cu ft

PROBLEM 4. RETURN ON INVESTMENT FOR CHLORINE RECOVERY SYSTEM

The off-gas from a chloral production unit contains 15 vol % Cl_2, 75 vol % HCl, and 10 vol % $EtCl_2$. This gas is produced at a rate of 150 cfm based on 70°F and 2 psig. It has been proposed to recover part of the Cl_2 by absorption and reaction in a partially chlorinated alcohol (PCA). The off-gas is to pass continuously through a packed absorption tower countercurrent to the PCA, where Cl_2 is absorbed and partially reacts with the PCA. The gas leaving the top of the tower passes through an alcohol condenser and thence to an existing HCl recovery unit.

The reaction between absorbed Cl_2 and the PCA is slow, and only part of the absorbed Cl_2 reacts in the tower. Part of this PCA from the bottom of the tower is sent to a retention system where the reaction is given time to approach equilibrium. The rest of the PCA is sent to the chloral production unit. Ethyl alcohol is added to the PCA going to the retention system. The PCA is recycled from the retention system to the top of the absorption column, and the ethyl alcohol is added at a rate sufficient to keep the recycle rate and recycle concentration constant.

Your preliminary calculations have set the optimum conditions of operations, and all costs have been determined except the cost for the absorption tower. Using the following data and information, determine the yearly per cent return on the capital expenditure:

The gases leaving the top of the tower contain 2 vol % Cl_2 (on the basis of no PCA vapors present in the gas).

The PCA entering the top of the tower contains 0.01 mole % free Cl_2.

The PCA leaving the bottom of the tower contains 0.21 mole % free Cl_2.

The recycle rate is 200 gpm (entering the top of the absorption tower).

The gas rate at the top of the column is 27.2 lb mole/hr.

The PCA entering the top of the tower has a density of 68.5 lb/cu ft and an average molecular weight of 70.

The column is operated at a temperature of 35°C and a pressure of 1 atm.

The gases enter the bottom of the tower at 70°F and 2 psig.

No Cl_2 is absorbed in the alcohol condenser.

The column is packed with 1-in. porcelain Raschig rings, and a porcelain tower is used.

Laboratory tests with a small column packed with Raschig rings have been conducted. These tests were carried out at 35°C using PCA and off-gas having the same concentrations as those in your proposed design. These data have been scaled up to apply to 1-in. Raschig rings and are applicable to your column. The results are given in Table 4.

TABLE 4

m_2G_2/L_2 based on conditions at dilute end of column	*Height of a transfer unit (log-mean method), ft*
0.178	3.6
0.571	4.8
1.04	6.2
1.53	7.6

The absorption of Cl_2 in the PCA follows Henry's law, and the following relation may be used for determining the number of transfer units:

$$N_t = \frac{y_1 - y_2}{\Delta y_m}$$

where Δy_m = log-mean driving force $= \dfrac{\Delta y_1 - \Delta y_2}{\ln (\Delta y_1/\Delta y_2)}$

$\Delta y_1 = y_1 - y_1^*$

$\Delta y_2 = y_2 - y_2^*$

Equilibrium data for Cl_2 and the PCA at 35°C and 1 atm are given in Table 5. These data apply over the entire length of the column.

TABLE 5

Free Cl_2 in PCA, x, mole %	*Free Cl_2 in gas (based on PCA vapor-free gas), y, mole %*
0.1	2.0
0.2	4.0
0.3	6.0

The maximum allowable velocity (based on conditions of the gas at the inlet to the tower) is 1.5 fps. The column will operate at 60 per cent of the maximum allowable velocity.

Necessary cost data are given in the following:

1. Tower:

Diameter, in.	12	18	24	30	36	42
Porcelain, \$/ft of length	70	100	135	180	230	285
Top or bottom heads, porcelain, each	60	85	115	150	190	235

2. Tower packing. One-inch Raschig rings, porcelain = \$5.00 per cubic foot.
3. Capital expenditure minus cost of absorption tower = \$11,000.
4. Net annual savings (taking alcohol loss and all other costs, such as interest, rent, taxes, insurance, depreciation, maintenance, and other overhead expenses into consideration) = \$6,000.

NOTE: This \$6,000 has been determined by including an accurate estimate of the absorption-tower cost and can be taken as the actual net savings.

Reference. AIChE Student Contest Problem, 1949.

Nomenclature for Prob. 4

G = molar gas flow, moles/hr
L = molar liquid flow, moles/hr
m = slope of equilibrium curve, y/x
N_t = number of transfer units
y = mole fraction of chlorine in gas
y^* = equilibrium mole fraction of chlorine in gas

Subscripts

1 = bottom of tower
2 = top of tower

PROBLEM 5. ECONOMIC ANALYSIS OF CHLORINE RECOVERY SYSTEM

The data shown in Table 6 have been obtained for a chlorine recovery system in which all values have been determined at the optimum operating conditions of retention time and recycle rates.

TABLE 6

Mole % Cl_2 in exit gas	Total capital expenditure, dollars	Total annual operating costs (fixed costs, production costs, overhead, etc.), dollars	Gross annual savings by using process, dollars
0.2	92,000	84,000	114,000
1.0	76,000	79,000	111,000
2.0	68,000	74,000	105,000
5.0	53,000	67,000	83,000
10.0	34,000	59,000	47,000

Determine the following:

1. The per cent Cl_2 in exit gas at break-even point.
2. The maximum net annual savings and per cent Cl_2 in exit gas where it occurs.
3. The maximum per cent return on the capital expenditure and per cent Cl_2 in exit gas where it occurs.
4. Which investment would you recommend and why?

Reference. AIChE Student Contest Problem, 1949.

PROBLEM 6. OPTIMUM THICKNESS OF INSULATION

Insulation is to be purchased for 3 miles of 10-in.-OD pipe carrying saturated steam at 250°F. The average air temperature for the year for the surroundings is 45°F.

It is estimated that the life period of the installation will be 20 years with negligible scrap value. The sum of fixed charges excluding depreciation is 10 per cent, and maintenance is estimated to be 2 per cent annually.

One company has submitted a bid which includes installation at a cost of $\$0.05D^{1.3}$ per linear foot, where D is the outside diameter of the lagging in inches. Using the following data and equations, what thickness of insulation should be used for this job in order to give a 50 per cent return on the full investment?

The line will be in continuous service 365 days/year. The steam is valued at $0.33 per 1000 lb. The thermal conductivity of the lagging is 0.04 Btu/(hr)(sq ft)(°F/ft). Steam-film and pipe resistance may be neglected.

Heat losses by conduction and convection from the surface may be calculated by use of the equation

$$h_c = 0.42 \left(\frac{\Delta t_s}{D_o'}\right)^{0.25}$$

where Δt_s = temperature difference between surface of lagging and air, °F
D_o = OD, in.
h_c = Btu/(hr)(sq ft)(°F)

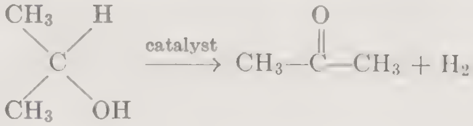
An average value of $h_r = 1.2$ Btu/(hr)(sq ft)(°F) may be used to determine heat losses by radiation. This is an adjusted value such that total heat loss per hour may be calculated by the equation

$$Q = (h_c + h_r)A\ \Delta t_s$$

A mathematical setup with all necessary numbers and a description of the method for final solution will be satisfactory.

PROBLEM 7. CAPACITY OF PLANT FOR PRODUCING ACETONE FROM ISOPROPANOL

Acetone is produced by the dehydrogenation of isopropanol according to the following reaction:



The reverse of the above reaction can be neglected.

The catalyst used for the process decreases in activity as the amount of isopropanol fed increases. This effect on the reaction rate is expressed in the following:

$$k = \frac{0.000254NT}{V}\left(2.46 \ln \frac{1}{1-\alpha} - \alpha\right)$$

where α = fraction of isopropanol converted to acetone and side products
= (moles isopropanol converted)/(moles isopropanol supplied)
k = reaction-rate constant, sec^{-1}
N = lb mole of isopropanol fed to converter per hour
T = absolute temperature, °R
V = catalyst volume, cu ft

The feed rate of isopropanol (N) is maintained constant throughout the entire process.

The fresh catalyst has an activity such that $k = 0.30\ \text{sec}^{-1}$.

After 10,000 lb of isopropanol per cubic foot of catalyst has been fed, $k = 0.15\ \text{sec}^{-1}$.

A plot of *log k versus total isopropanol fed as pounds mole* is a straight line.

The maximum production of acetone is 76.1 lb mole/hr. This maximum production can be considered as at zero time (i.e., when $k = 0.30\ \text{sec}^{-1}$).

A constant temperature of 572°F and a constant pressure of 1 atm are maintained throughout the entire process.

The catalyst volume $V = 250$ cu ft.

$$\text{Efficiency} = \frac{\text{moles acetone produced}}{\text{moles isopropanol consumed}}(100) = 98\%\ \text{at } 572°\text{F}$$

The catalyst can be reactivated to its original activity by shutting the unit down for two 24-hr days.

The catalyst will be thrown away after the last operating period each year.

The unit will operate 350 days/year (this includes reactivation shutdowns). The other 15 days are used for repairs and replacing the old catalyst.

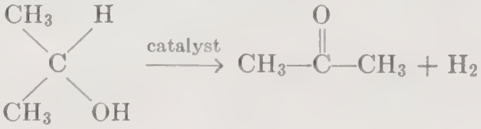
If nine catalyst reactivations are used per year, what will the production of acetone be in pounds per year?

Outline your method of solution. The actual mathematical calculations are not necessary.

Reference. AIChE Student Contest Problem, 1948.

PROBLEM 8. EQUIPMENT DESIGN FOR THE PRODUCTION OF ACETONE FROM ISOPROPANOL

You are designing a plant for the production of acetone from isopropanol. Acetone is produced according to the following reaction:



The reaction can be assumed as irreversible.

The catalyst used in this process decreases in activity as the process proceeds. This effect on the reaction rate can be expressed as follows:

$$k = \frac{0.000254}{V} NT \left(2.46 \ln \frac{1}{1 - \alpha} - \alpha\right)$$

where α = fraction of isopropanol converted to acetone and side products
= (moles isopropanol converted)/(moles isopropanol supplied)
k = reaction-rate constant, sec^{-1}
N = lb mole of isopropanol fed to converter per hour
T = absolute temperature, °R
V = catalyst volume, cu ft

The catalyst must be regenerated periodically throughout the operation.

The fresh catalyst has an activity such that $k = 0.30 \text{ sec}^{-1}$.

The products from the reactor (unconverted isopropanol, acetone, side products, and some water from the impure isopropanol feed) are sent to a continuous distillation column where purified acetone is removed.

A distillation column, calandria, and condenser are now available in your plant, and you are to determine if these can be used for the purification step.

Using the following data, determine whether or not the column, calandria, and condenser are usable. If these are not satisfactory, determine the purchase cost of the necessary equipment. Do not buy any new equipment unless you need it. However, the present equipment may be used in another part of the plant at a later date.

Feed rate of isopropanol (N) is kept constant at 97 moles of isopropanol per hour during the entire operation.

A constant temperature of 572 F and a constant pressure of 1 atm are maintained throughout the entire operation.

The catalyst volume V = 250 cu ft.

$$\text{Efficiency of conversion} = \frac{\text{moles acetone produced}}{\text{moles isopropanol consumed}} (100) = 98\% \text{ at } 572 \text{ F}$$

The present distillation tower contains 50 actual plates. Your calculations have indicated that a reflux ratio of 1:1 will allow 98 per cent of the acetone to be removed, assuming a 40 per cent plate efficiency. The product material may be assumed as 100 per cent acetone. These conditions are satisfactory, and you have made calculations at these conditions, giving the results shown in Table 7.

TABLE 7

Per 1000 lb/hr of acetone distilled over and removed as product

Column cross-sectional area, sq ft	6.4 (based on 12-in. plate spacing and 2-in. liquid depth)
Condenser area, sq ft	220
Steam, lb/hr	1100

The over-all heat-transfer coefficient in the calandria is 250 Btu/(hr)(sq ft)(°F).

Saturated steam is available at 50 psig. Neglect any sensible heat transfer from steam condensate to boiling liquid. The temperature-difference driving force Δt in the calandria may be assumed to be 90°F.

Your calculations have indicated that the present condenser on the column is satisfactory and may be used for this process.

The necessary data on the present equipment are given in Table 8.

TABLE 8

Number of plates in column	50
Column diameter	72 in.
Plate spacing	12 in.
Liquid depth on each plate	2 in.
Calandria heat-transfer area	104 sq ft
Calandria shell working pressure	60 psig

Table 9 shows the cost data for any new equipment which must be purchased.

TABLE 9. STEEL HEAT EXCHANGERS

Surface, sq ft	*Cost, $/sq ft*
100	14.00
200	10.50
300	8.50
500	6.50

Steel Distillation Column

Estimate on the basis of $25.00 per square foot of tray area. Column diameters should be even multiples of 6 in.

Reference. AIChE Student Contest Problem, 1948.

PROBLEM 9. QUICK-ESTIMATE DESIGN OF DEBUTANIZER

You are the chief design engineer at a large petroleum refinery. The head projects engineer has asked you to make a preliminary design estimate for a proposed debutanizer. You are to present the following preliminary information to a group meeting 3 hr from now:

1. Number of plates for proposed debutanizer column
2. Diameter of proposed column
3. Outside tube area required for heating coils in reboiler (coils to contain saturated steam at 250 psia, and average heat of vaporization of hydrocarbons in reboiler may be taken as 5000 cal/g mole)

The following information has been supplied you by the projects engineer:

Charge stock from catalytic cracker to debutanizer = 5620 BPSD.
Debutanizer to operate at 165 psia.
Two fractions are to be obtained—OVHD and BTMS.
OVHD is to contain 98.5 per cent of the butanes and lighter components with a contamination of 1.5 mole % pentanes and pentenes.
The debutanizer must fractionate between NC_4 and IC_5.

Table 10. Debutanizer Charge Stock from Catalytic Cracker

°API (60°F) = 100.3
Viscosity = 42 SSU at 120°F

Component	Mole %	Molecular weight
C_2''	0.1	28
C_2	1.2	30
H_2S	2.1	34
C_3''	16.3	42
C_3	6.9	44
IC_4''	6.5	56
NC_4''	14.3	56
IC_4	10.8	58
NC_4	3.9	58
C_5''	11.9	70
IC_5	9.7	72
NC_5	2.3	72
C_6	11.8	86
C_7	2.1	96
C_8	0.1	112
	100.0	

A search through your debutanizer-design card file gives the information shown in Cards A to C.

Card A Debutanizer: 30 trays

Feed 574 BPSD		Reflux 635 BPSD	OVHD 354 BPSD		BTMS 220 BPSD	
5897 lb/hr		5630 lb/hr	3114 lb/hr		2783 lb/hr	
84.6 moles/hr		100.6 moles/hr	56.0 moles/hr		28.6 moles/hr	
Mole %		*Composition same as OVHD*	*Mole %*		*Mole %*	
C_3''	12.4	Reflux ratio = 1.8:1	C_3''	18.8	C_4's	1.4
C_3	6.1		C_3	9.2	C_5—400°F	98.6
C_4's	47.9		C_4's	71.6		100.0
C_5—400°F	33.6		C_5—400°F	0.4		
	100.0			100.0		
°API = 68.8		°API = 100.7	°API = 100.7		°API = 39.7	
Basis: feed		119 mole %	66.2 mole %		33.8 mole %	

Card B Values of K at 165 psia

Listings derived principally from the data of Scheibel and Jenny, *Ind. Eng. Chem.*, **37**:80 (1945).

Hydrocarbon	*260°F*	*280°F*	*285°F*	*290°F*	*300°F*
n-Butane	1.75	2.00	2.06	2.13	2.25
n-Pentene	1.15	1.30	1.34	1.39	1.47
Isopentane	1.03	1.19	1.23	1.28	1.37
n-Pentane	0.90	1.06	1.11	1.16	1.25
n-Hexane	0.46	0.58	0.61	0.64	0.70
n-Heptane	0.24	0.31	0.32	0.35	0.39
n-Octane	0.13	0.17	0.18	0.19	0.21

Card C Recommended over-all heat-transfer coefficients (based on outside coil heating area)

	Debutanizer service	*Transfer rate, Btu/(hr)(sq ft)(°F)*
Condenser	Butane to water	100–110
Reboiler	Gasoline to steam	120–140
Reboiler	Gasoline to hot oil	50–75
Exchanger	Gasoline to gasoline	80
Preheater	Gasoline to steam	110–120
Cooler	Gasoline to water	75–90

Reference. L. J. Coulthurst, *Chem. Eng. Progr.*, **44**:257 (1948).

PROBLEM 10. ECONOMIC ANALYSIS OF FORMALDEHYDE-PENTAERYTHRITOL PLANT

You are a member of firm doing consulting work on chemical engineering design. The G. I. Treyz Chemical Company of Cooks Falls, N.Y., has asked your firm to determine the advisability of adding a pentaerythritol production unit to its present formaldehyde plant. You have been sent to Cooks Falls to analyze the situation and obtain the necessary details.

A conference with G. Victor Treyz, owner of the plant, supplies you with the following information:

The present formaldehyde plant cost $500,000 and is in satisfactory operating condition. It produces formaldehyde by the oxidation of methanol. The yearly fixed charges (interest, rent, taxes, insurance, and depreciation) at the plant amount to 15 per cent of the initial investment.

The plant capacity is 100,000 lb of formalin (37.2 per cent HCHO, 8 per cent CH_3OH, and 54.8 per cent H_2O by weight) per day.

Miscellaneous costs (salaries, labor, office expenses, lab supplies, maintenance, repairs, communication, sales, silver catalyst replacement, etc.) amount to $150,000 per year.

The over-all efficiency of conversion of methanol into formaldehyde equals 80 per cent; i.e., 0.8 lb of CH_3OH converted to HCHO per pound of CH_3OH decomposed.

The total cost of utilities (fuel, electricity, steam, water, etc.) equals 5 per cent of the total cost of producing the formaldehyde.

Mr. Treyz has included all the smaller costs such as insurance benefits, etc., in the overhead cost so that the total cost of the present operation is the sum of fixed charges, overhead cost, utilities, and methanol.

The proposed PE plant is to produce 6000 lb of final pentaerythritol per day. The basic reaction involving lime, acetaldehyde, and formaldehyde can be assumed to be going to completion. Only 70 per cent of the PE produced in the reaction is obtained as the final product. Any costs due to the presence of excess $Ca(OH)_2$ can be neglected. The calcium formate formed must be discarded.

The initial installed cost of the proposed plant is $400,000. It can be assumed that the yearly cost of the new operation minus raw-materials costs will be 40 per cent of the initial installed cost. This 40 per cent includes fixed charges, overhead, utilities, and all other expenses except raw materials.

Both plants operate 350 days/year.

Mr. Treyz feels he can sell 6000 lb of PE per day at the present market price. He can also sell 100,000 lb of formaldehyde per day, but he is willing to make the new investment if it will give him better than a 30 per cent yearly return on the PE initial plant investment.

Following is a list of prices supplied by Mr. Treyz. All these prices are f.o.b. Cooks Falls, N.Y., and they are to be used for the cost estimate.

Methanol, carload lots	$ 0.33/gal = $0.05/lb
Formaldehyde, 37.2% HCHO, 8% CH_3OH	0.043/lb
Acetaldehyde	0.11/lb
Lime as pure CaO	10.00/ton
Pentaerythritol	0.33/lb

From the preceding information, determine the following:

(*a*) The present profit per year on the formaldehyde unit.
(*b*) The total profit per year if the PE unit were in operation.
(*c*) Yearly per cent return on the PE initial plant investment.
(*d*) Should the Treyz Company make the investment?

APPENDIX B

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TABLE 1. CONVERSION FACTORS AND CONSTANTS

Length

1 inch	2.54 centimeters
1 foot	30.48 centimeters
1 yard	91.44 centimeters
1 meter	100.00 centimeters
1 meter	39.37 inches
1 micron	10^{-6} meter
1 mile	5280 feet
1 kilometer	0.6214 mile

Mass

1 pound *	16.0 ounces
1 pound *	453.6 grams
1 pound *	7000 grains
1 ton (short)	2000 pounds *
1 kilogram	1000 grams
1 kilogram	2.205 pounds *

* Avoirdupois.

Volume

1 cubic inch	16.39 cubic centimeters
1 liter	61.03 cubic inches
1 liter	1.057 quarts
1 cubic foot	28.32 liters
1 cubic foot	1728 cubic inches
1 cubic foot	7.481 U.S. gallons
1 U.S. gallon	4.0 quarts
1 U.S. gallon	3.785 liters
1 U.S. bushel	1.244 cubic feet

Density

1 gram per cubic centimeter	62.43 pounds per cubic foot
1 gram per cubic centimeter	8.345 pounds per U.S. gallon

1 gram mole of an ideal gas at 0°C and 760 mm Hg is equivalent to 22.414 liters

1 pound mole of an ideal gas at 0°C and 760 mm Hg is equivalent to 359.0 cubic feet

Density of dry air at 0°C and 760 mm Hg	1.293 grams per liter = 0.0807 pound per cubic foot
Density of mercury	13.6 grams per cubic centimeter (at −2°C)

Pressure

1 pound per square inch	2.04 inches of mercury
1 pound per square inch	51.71 millimeters of mercury
1 pound per square inch	2.31 feet of water
1 atmosphere	760 millimeters of mercury
1 atmosphere	2116.2 pounds per square foot
1 atmosphere	33.93 feet of water
1 atmosphere	29.92 inches of mercury
1 atmosphere	14.7 pounds per square inch

TABLE 1. CONVERSION FACTORS AND CONSTANTS (*Continued*)

Temperature Scales

Degrees Fahrenheit (F)	1.8 (degrees C) + 32
Degrees centigrade (C)	1/1.8 (degrees F − 32)
Degrees Kelvin (K)	degrees C + 273.16
Degrees Rankine (R)	degrees F + 459.7

Power

1 kilowatt	737.56 foot-pounds force per second
1 kilowatt	56.87 Btu per minute
1 kilowatt	1.341 horsepower
1 horsepower	550 foot-pounds force per second
1 horsepower	0.707 Btu per second
1 horsepower	745.7 watts

Heat, Energy, and Work Equivalents

	Cal	Btu	Ft-lb	Kwhr	Hp-hr	Joules	Liter-atm
Cal	1	3.97×10^{-3}	3.086	1.162×10^{-6}	1.558×10^{-6}	4.1840	4.129×10^{-2}
Btu	252	1	778.16	2.930×10^{-4}	3.930×10^{-4}	1055	10.41
Ft-lb	0.3241	1.285×10^{-3}	1	3.766×10^{-7}	5.0505×10^{-7}	1.356	1.338×10^{-2}
Kwhr	860,565	3412.8	2.655×10^{6}	1	1.341	3.60×10^{6}	35,534.3
Hp-hr	641,615	2545.0	1.980×10^{6}	0.7455	1	2.685×10^{6}	26,494
Joules	0.239	9.478×10^{-4}	0.7376	2.773×10^{-7}	3.725×10^{-7}	1	9.869×10^{-3}
Liter-atm	24.218	9.604×10^{-2}	74.73	2.815×10^{-5}	3.774×10^{-5}	101.33	1

Constants

e	2.7183
π	3.1416
Gas-law constants:	
R	1.987 (cal)/(g mole)(°K)
R	82.06 (cu cm)(atm)/(g mole)(°K)
R	10.73 (lb/sq in.)(cu ft)/(lb mole)(°R)
R	0.730 (atm)(cu ft)/(lb mole)(°R)
R	1545.0 (lb/sq ft)(cu ft)/(lb mole)(°R)
g_c	32.17 (ft)(lb mass)/(sec)(sec)(lb-force)

Analysis of Air

By weight: oxygen, 23.2%; nitrogen, 76.8%
By volume: oxygen, 21.0%; nitrogen, 79.0%
Average molecular weight of air on above basis = 28.84 (usually rounded off to 29)
True molecular weight of dry air (including argon) = 28.96

Viscosity

1 centipoise	0.01 g/(sec)(cm)
1 centipoise	0.000672 lb/(sec)(ft)
1 centipoise	2.42 lb/(hr)(ft)

TABLE 2. AVERAGE SERVICE LIVES (YEARS) FOR EQUIPMENT ITEMS IN THE CHEMICAL INDUSTRY *

Acids	
Acetic:	
Blowcases, cast-iron and copper	3
Columns, fractionating	8
Condensers:	
Copper	10
Duriron	14
Lead	6
Motors	14
Pipes:	
Acid:	
Copper	10
Rubber	8
Aluminum	3
Glass	5
Water	10
Pots	17
Pumps, vacuum	7
Receivers, acid, for product (stoneware)	20
Receivers, acid (stoneware)	14
Scrubbers (stoneware)	14
Stills:	
Cast iron	12
Refining, copper	14
Refining, heating coil	3
Tanks, storage:	
Steel	12
Wood	25
Muriatic:	
Air lifts (hard rubber)	10
Cars, tank	10
Coolers	10
Elevators, bucket	10
Exhausters (rubber-lined)	8
Flues (earthenware)	10
Furnaces, Mannheim	8
Furnaces, pot and muffle	10
Furnaces, retort	8
Grinders and coolers, salt cake	12
Motors	14
Pipes:	
Acid (hard rubber)	7
Chemical ware	2
Oil	20
Water	4
Pots, condensing (earthenware)	7
Pumps and blowcases:	
Chemical ware-lined	3
Rubber-lined blowcase	5
Storage tanks (wooden, rubber-lined)	14
Tanks, sulfuric acid storage (steel)	20
Tourilles (silica)	10
Towers, absorbing	10
Nitric:	
Blowers (stoneware)	5
Blowcases (earthenware)	2
Condensers (duriron)	12
Condensers, S-bend (stoneware)	2
Elevators and conveyors (screw)	10
Flues, gas (Duriron)	8
Pans, niter cake (steel)	14
Pipes and fittings (earthenware, Duriron, lead)	2
Pumps, sulfuric (iron), centrifugal	5
Receivers (stoneware)	5
Retorts, 24-hour service	3
Tanks (steel)	10
Towers, condensing	9
Sulfuric (contact):	
Air lifts	14
Blowcases (cast iron and steel)	5
Blowers	20
Burners:	
Brimstone	10
Glens Falls	10
Other	15
Coke boxes	17
Combustion chambers, brimstone	10
Compressors, air	15
Contact mass, including plates and supports	17
Converters	14
Conveyors and elevators	10
Coolers:	
Drying acid	10
Gas	14
Gas, tower	10
Dust chambers (brick)	14
Filters, preliminary	11
Flues (iron)	13
Gauges, meters, pyrometers	14
Heaters, preliminary	14
Melters, brimstone	10
Motors	17

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* Income Tax Depreciation and Obsolescence—Estimated Useful Lives and Depreciation Rates, *U.S. Bureau of Internal Revenue Bull. F*, 1942.

TABLE 2. AVERAGE SERVICE LIVES (YEARS) FOR EQUIPMENT ITEMS IN THE CHEMICAL INDUSTRY (*Continued*)

Pipes, acid	10
Platinum, in catalyst	50
Pumps, acid (iron)	7
Pumps, acid (lead)	8
Separators	14
Sublimers, brimstone	10
Tank cars (steel)	12
Tanks:	
Roasted ore storage (steel)	20
Storage (lead)	20
Storage (steel)	17
Towers:	
Absorbing	9
Cooler, cold scrub	12
Dry	10
Oleum	10
Scrub	10
Transferrers	9

Alkalies

Absorbers	30
Bins:	
Charging	30
Storage	25
Classifiers	20
Compressors:	
For carbon dioxide	25
Chlorine dry gas	28
Concentrating and evaporating units (for potassium carbonate)	20
Concentrating units (ammonium chloride)	12
Conveyors	20
Coolers, brine	20
Dryers:	
Salt (calcium chloride)	16
Steam (bicarbonate of soda)	20
Evaporators, caustic soda (cast iron, magnesia-covered)	17
Feeder, lime	19
Filter wheel for causticizer	20
Flaker wheel with speed reducer	15
Furnaces (for calcining bicarbonate of soda into soda ash)	6
Kiln, lime	22
Pans, settler	20
Pots, cast iron	12
Pumps:	
Caustic soda (centrifugal type)	18
Chlorine dry gas	18
Receivers, vacuum	20
Recovery units	7
Retorts, cast iron	20
Scrubbers	35
Scrubbers, vacuum	20
Separators	20
Settling units (calcium chloride)	15
Slaker	21
Tanks:	
Ash storage	30
Bottom dissolver (caustic plant)	18
Dissolver and mixer	30
Feeder, steel	33
Filter wheel for causticizer	20
Lime	21
Mixing	25
Mud	33
Mud storage	30
Salt settling	20
Settling	33
Storage	30
Storage (weak caustic soda solution)	22
Thickener	25
Towers	25
Towers:	
Carbonating and precipitating	33
Distillation	33
Washing (for chlorine gas):	
Cast iron	20
Stone	22
Washers	37

Carbide and Carbon Products

Absorbers	10
Bagging machines	14
Barrels, tilting and tumbling	8
Breakers	12
Briquetting machines	18
Buckets, charging	8
Cells, chlorine	6
Charging machines	12
Chlorinators	12
Coke quenchers	15
Columns	8
Columns, ammonia	6
Concentrators (hydraulic type)	12
Condensers (closed type)	17
Containers, copper	9
Coolers	10
Coolers, after, fore, and inter	17

TABLE 2. AVERAGE SERVICE LIVES (YEARS) FOR EQUIPMENT ITEMS IN THE CHEMICAL INDUSTRY (*Continued*)

Crushers, gyratory, jaw and roll	12
Digesters	10
Dryers (rotary and tunnel types)	25
Evaporators	17
Fillers, bag	14
Furnaces:	
Electric, carbide, and metallurgical	20
Gas for heat-treating, torching, and branding	8
Preheating and welding	12
Generators, acetylene	12
Grinders	12
Holders, gas	25
Hydrators	12
Hydrolyzers	7
Incinerators	22
Kettles:	
Melting	6
Nitrating	6
Reducing	6
Salt	6
Steam-jacketed	6
Kilns:	
Calcining	22
Rotary	22
Vertical	28
Ladles	22
Mills	12
Mills, stamp	12
Mixers	12
Ovens, coke	17
Oxygen manifolds	20
Pans:	
Melting	6
Nitrating	6
Reducing	6
Steam-jacketed	6
Precipitators	18
Preheater	9
Press, filter	17
Pulverizers	12
Purifiers	18
Receivers, copper	9
Retorts	22
Saturators	12
Screens	12
Sifters	12
Stills (closed type)	17
Thickeners	17
Towers:	
Acid and reaction	5
Cooling	7
Carbonic Gas Products	
Absorbers, gas	16
Compressors:	
Air	22
Carbonic dry ice	6
Coolers, gas	15
Cylinders	25
Interchargers, heat	15
Liquefiers	14
Scrubbers, gas	16
Towers, purifier	15
Electrochemicals	
Absorbers	20
Air washers	20
Blowers, noncorrosive fumes	25
Burners, phosphorus	10
Cells, electrolytic	15
Centrifugals	25
Compressors, air	25
Compressors (gas pumps)	15
Condensers:	
Concrete construction	25
Steel, with tubes	20
Conveyors	20
Coolers:	
Lead-lined	15
Rotary	20
Crystallizers	15
Digesters, lead-lined	15
Dishes, silica	10
Dissolvers, lead-lined	15
Drainers, lead-lined	15
Dryers:	
Rotary tube	10
Vacuum	20
Drying pans, lead-lined	20
Dust collectors	15
Eggs, lead-lined	15
Elevators:	
Bucket and belt	15
Screw conveyors	10
Evaporating pans, steam-jacketed kettles	15

TABLE 2. AVERAGE SERVICE LIVES (YEARS) FOR EQUIPMENT ITEMS IN THE CHEMICAL INDUSTRY (*Continued*)

Evaporators:	
Lead-lined	15
Steam	15
Fans	20
Filter presses:	
Cast-iron plates	15
Steel leaves	20
Filters	20
Furnaces, electric	20
Heaters:	
Electric, hot plate	15
Electric, hot water	12
Hoppers, sheet metal	15
Kilns, rotary	15
Meter, liquid measuring	10
Metering equipment, electric	25
Mills, grinding	20
Mixers	20
Motor	20
Motor generator sets	20
Pipe, silica	4
Piping:	
Air, gas, steam, water	25
Corrosive matter	15
Pots:	
Caustic	18
Ceramics	15
Furnace (cast iron)	20
Melting (cast iron)	15
Pumps:	
Corrosive liquor	10
Water	20
Reactors, electrical	25
Regulators, temperature	10

Rotary converters	25
Scales	15
Scooper, bucket type	10
Speed reducers	12
Stills, lead	10
Stoker, to kiln	15
Tanks:	
Aluminum	15
Cast iron	25
Galvanized iron	15
Hot-water storage	15
Lead-lined	15
Steel or concrete-lined	15
Wooden, lead-lined	15
Towers, steel	20
Transformers	25
Troughs, silica	4

Oxygen

Columns	10
Compressors:	
Air	25
Nitrogen	20
Oxygen	20
Cylinder drying chambers	18
Cylinder testing apparatus	10
Cylinders	25
Dryers, oxygen	14
Engines, expansion	25
Holders, oxygen	25
Oxygen filling manifolds	12
Towers:	
Cooling	12
Decarbonizing (steel drum type)	16

TABLE 3. VISCOSITIES OF GASES *

Coordinates for use with Fig. B-1

No.	Gas	X	Y	No.	Gas	X	Y
1	Acetic acid	7.7	14.3	29	Freon 113	11.3	14.0
2	Acetone	8.9	13.0	30	Helium	10.9	20.5
3	Acetylene	9.8	14.9	31	Hexane	8.6	11.8
4	Air	11.0	20.0	32	Hydrogen	11.2	12.4
5	Ammonia	8.4	16.0	33	$3H_2 + 1N_2$	11.2	17.2
6	Argon	10.5	22.4	34	Hydrogen bromide	8.8	20.9
7	Benzene	8.5	13.2	35	Hydrogen chloride	8.8	18.7
8	Bromine	8.9	19.2	36	Hydrogen cyanide	9.8	14.9
9	Butene	9.2	13.7	37	Hydrogen iodide	9.0	21.3
10	Butylene	8.9	13.0	38	Hydrogen sulfide	8.6	18.0
11	Carbon dioxide	9.5	18.7	39	Iodine	9.0	18.4
12	Carbon disulfide	8.0	16.0	40	Mercury	5.3	22.9
13	Carbon monoxide	11.0	20.0	41	Methane	9.9	15.5
14	Chlorine	9.0	18.4	42	Methyl alcohol	8.5	15.6
15	Chloroform	8.9	15.7	43	Nitric oxide	10.9	20.5
16	Cyanogen	9.2	15.2	44	Nitrogen	10.6	20.0
17	Cyclohexane	9.2	12.0	45	Nitrosyl chloride	8.0	17.6
18	Ethane	9.1	14.5	46	Nitrous oxide	8.8	19.0
19	Ethyl acetate	8.5	13.2	47	Oxygen	11.0	21.3
20	Ethyl alcohol	9.2	14.2	48	Pentane	7.0	12.8
21	Ethyl chloride	8.5	15.6	49	Propane	9.7	12.9
22	Ethyl ether	8.9	13.0	50	Propyl alcohol	8.4	13.4
23	Ethylene	9.5	15.1	51	Propylene	9.0	13.8
24	Fluorine	7.3	23.8	52	Sulfur dioxide	9.6	17.0
25	Freon 11	10.6	15.1	53	Toluene	8.6	12.4
26	Freon 12	11.1	16.0	54	2,3,3-Trimethylbutane	9.5	10.5
27	Freon 21	10.8	15.3	55	Water	8.0	16.0
28	Freon 22	10.1	17.0	56	Xenon	9.3	23.0

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* J. H. Perry, "Chemical Engineers' Handbook," 3d ed., McGraw-Hill Book Company, Inc., New York, 1950.

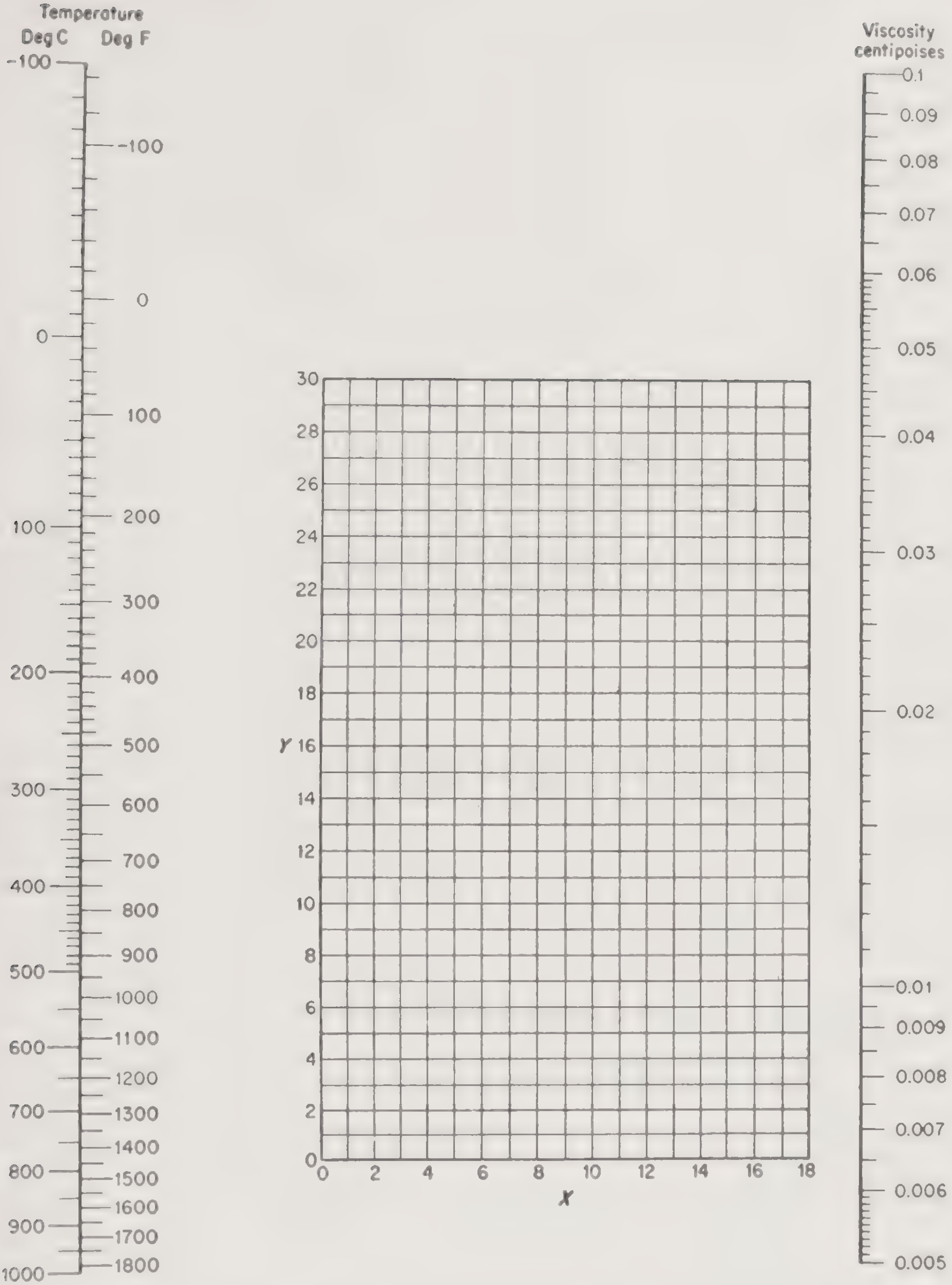

FIG. B-1. Viscosities of gases at 1 atm. (For coordinates see Table 3.)

TABLE 4. VISCOSITIES OF LIQUIDS *

Coordinates for use with Fig. B-2

No.	Liquid	X	Y	No.	Liquid	X	Y
1	Acetaldehyde	15.2	4.8	56	Freon 22	17.2	4.7
2	Acetic acid, 100%	12.1	14.2	57	Freon 113	12.5	11.4
3	Acetic acid, 70%	9.5	17.0	58	Glycerol, 100%	2.0	30.0
4	Acetic anhydride	12.7	12.8	59	Glycerol, 50%	6.9	19.6
5	Acetone, 100%	14.5	7.2	60	Heptene	14.1	8.4
6	Acetone, 35%	7.9	15.0	61	Hexane	14.7	7.0
7	Allyl alcohol	10.2	14.3	62	Hydrochloric acid, 31.5%	13.0	16.6
8	Ammonia, 100%	12.6	2.0	63	Isobutyl alcohol	7.1	18.0
9	Ammonia, 26%	10.1	13.9	64	Isobutyric acid	12.2	14.4
10	Amyl acetate	11.8	12.5	65	Isopropyl alcohol	8.2	16.0
11	Amyl alcohol	7.5	18.4	66	Kerosene	10.2	16.9
12	Aniline	8.1	18.7	67	Linseed oil, raw	7.5	27.2
13	Anisole	12.3	13.5	68	Mercury	18.4	16.4
14	Arsenic trichloride	13.9	14.5	69	Methanol, 100%	12.4	10.5
15	Benzene	12.5	10.9	70	Methanol, 90%	12.3	11.8
16	Brine, $CaCl_2$, 25%	6.6	15.9	71	Methanol, 40%	7.8	15.5
17	Brine, NaCl, 25%	10.2	16.6	72	Methyl acetate	14.2	8.2
18	Bromine	14.2	13.2	73	Methyl chloride	15.0	3.8
19	Bromotoluene	20.0	15.9	74	Methyl ethyl ketone	13.9	8.6
20	Butyl acetate	12.3	11.0	75	Naphthalene	7.9	18.1
21	Butyl alcohol	8.6	17.2	76	Nitric acid, 95%	12.8	13.8
22	Butyric acid	12.1	15.3	77	Nitric acid, 60%	10.8	17.0
23	Carbon dioxide	11.6	0.3	78	Nitrobenzene	10.6	16.2
24	Carbon disulfide	16.1	7.5	79	Nitrotoluene	11.0	17.0
25	Carbon tetrachloride	12.7	13.1	80	Octane	13.7	10.0
26	Chlorobenzene	12.3	12.4	81	Octyl alcohol	6.6	21.1
27	Chloroform	14.4	10.2	82	Pentachloroethane	10.9	17.3
28	Chlorosulfonic acid	11.2	18.1	83	Pentane	14.9	5.2
29	Chlorotoluene, ortho	13.0	13.3	84	Phenol	6.9	20.8
30	Chlorotoluene, meta	13.3	12.5	85	Phosphorus tribromide	13.8	16.7
31	Chlorotoluene, para	13.3	12.5	86	Phosphorus trichloride	16.2	10.9
32	Cresol, meta	2.5	20.8	87	Propionic acid	12.8	13.8
33	Cyclohexanol	2.9	24.3	88	Propyl alcohol	9.1	16.5
34	Dibromoethane	12.7	15.8	89	Propyl bromide	14.5	9.6
35	Dichloroethane	13.2	12.2	90	Propyl chloride	14.4	7.5
36	Dichloromethane	14.6	8.9	91	Propyl iodide	14.1	11.6
37	Diethyl oxalate	11.0	16.4	92	Sodium	16.4	13.9
38	Dimethyl oxalate	12.3	15.8	93	Sodium hydroxide, 50%	3.2	25.8
39	Diphenyl	12.0	18.3	94	Stannic chloride	13.5	12.8
40	Dipropyl oxalate	10.3	17.7	95	Sulfur dioxide	15.2	7.1
41	Ethyl acetate	13.7	9.1	96	Sulfuric acid, 110%	7.2	27.4
42	Ethyl alcohol, 100%	10.5	13.8	97	Sulfuric acid, 98%	7.0	24.8
43	Ethyl alcohol, 95%	9.8	14.3	98	Sulfuric acid, 60%	10.2	21.3
44	Ethyl alcohol, 40%	6.5	16.6	99	Sulfuryl chloride	15.2	12.4
45	Ethyl benzene	13.2	11.5	100	Tetrachloroethane	11.9	15.7
46	Ethyl bromide	14.5	8.1	101	Tetrachloroethylene	14.2	12.7
47	Ethyl chloride	14.8	6.0	102	Titanium tetrachloride	14.4	12.3
48	Ethyl ether	14.5	5.3	103	Toluene	13.7	10.4
49	Ethyl formate	14.2	8.4	104	Trichloroethylene	14.8	10.5
50	Ethyl iodide	14.7	10.3	105	Turpentine	11.5	14.9
51	Ethylene glycol	6.0	23.6	106	Vinyl acetate	14.0	8.8
52	Formic acid	10.7	15.8	107	Water	10.2	13.0
53	Freon 11	14.4	9.0	108	Xylene, ortho	13.5	12.1
54	Freon 12	16.8	5.6	109	Xylene, meta	13.9	10.6
55	Freon 21	15.7	7.5	110	Xylene, para	13.9	10.9

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* J. H. Perry, "Chemical Engineers' Handbook," 3d ed., McGraw-Hill Book Company, Inc., New York, 1950.

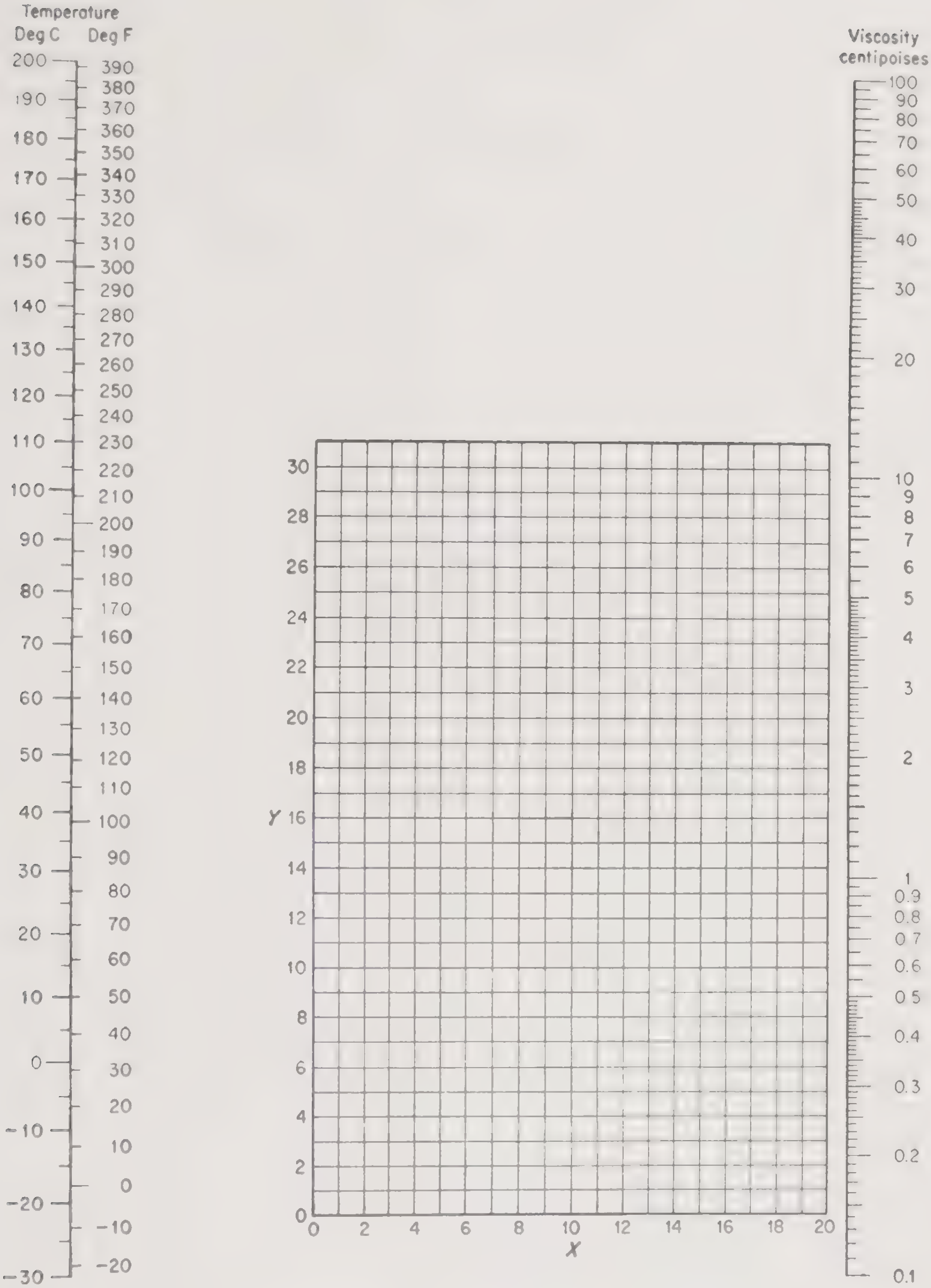

FIG. B-2. Viscosities of liquids at 1 atm. (For coordinates see Table 4.)

TABLE 5. DENSITY, VISCOSITY, AND THERMAL CONDUCTIVITY OF WATER

Temperature, °F	Density of liquid water, lb/cu ft	Viscosity of water,* centipoises	Thermal conductivity of water,† Btu/(hr)(sq ft)(°F/ft)
32	62.42	1.794	0.320
40	62.43	1.546	0.326
50	62.42	1.310	0.333
60	62.37	1.129	0.340
70	62.30	0.982	0.346
80	62.22	0.862	0.352
90	62.11	0.764	0.358
100	62.00	0.684	0.363
110	61.86	0.616	0.367
120	61.71	0.559	0.371
130	61.55	0.511	0.375
140	61.38	0.470	0.378
150	61.20	0.433	0.381
160	61.00	0.401	0.384
170	60.80	0.372	0.386
180	60.58	0.347	0.388
190	60.36	0.325	0.390
200	60.12	0.305	0.392
210	59.88	0.287	0.393
212	59.83	0.284	0.393

* Calculated by W. L. Badger and W. L. McCabe from data in "International Critical Tables."

† E. Schmidt and W. Sellschopp, *Forsch. Gebiete Ingenieurw.*, **3**:227–286 (1932).

TABLE 6. THERMAL CONDUCTIVITY OF METALS *

Metal	k, Btu/(hr)(sq ft)(°F/ft)		
	At 32°F	At 212°F	At 572°F
Aluminum	117	119	133
Brass (70-30)	56	60	66
Cast iron	32	30	26
Copper	224	218	212
Lead	20	19	18
Nickel	36	34	32
Silver	242	238	. . .
Steel (mild)	. . .	26	25
Tin	36	34	. . .
Wrought iron	. . .	32	28
Zinc	65	64	59

* J. H. Perry, "Chemical Engineers' Handbook," 3d ed., McGraw-Hill Book Company, Inc., New York, 1950.

TABLE 7. THERMAL CONDUCTIVITY OF NONMETALLIC SOLIDS *

Material	Temperature, °F	k, Btu/(hr)(sq ft)(°F/ft)
Asbestos-cement boards	68	0.43
Bricks:		
Building	68	0.40
Fire clay	392	0.58
	1832	0.95
Sil-O-Cel	400	0.042
Calcium carbonate (natural)	86	1.3
Calcium sulfate (building plaster)	77	0.25
Celluloid	86	0.12
Concrete (stone)	. . .	0.54
Cork board	86	0.025
Felt (wool)	86	0.03
Glass (window)	. . .	0.3–0.61
Rubber (hard)	32	0.087
Wood (across grain):		
Maple	122	0.11
Oak	59	0.12
Pine	59	0.087

* J. H. Perry, "Chemical Engineers' Handbook," 3d ed., McGraw-Hill Book Company, Inc., New York, 1950.

TABLE 8. THERMAL CONDUCTIVITY OF LIQUIDS *

Liquid	Temperature, °F	k, Btu/(hr)(sq ft)(°F/ft)
Acetic acid:		
100%	68	0.099
50%	68	0.20
Acetone	86	0.102
	167	0.095
Benzene	86	0.092
	140	0.087
Ethyl alcohol:		
100%	68	0.105
	122	0.087
40%	68	0.224
Ethylene glycol	32	0.153
Glycerol:		
100%	68	0.164
	212	0.164
40%	68	0.259
n-Heptane	86	0.081
Kerosene	68	0.086
Methyl alcohol:		
100%	68	0.124
	122	0.114
40%	68	0.234
n-Octane	86	0.083
Sodium chloride brine, 25%	86	0.330
Sulfuric acid:		
90%	86	0.210
30%	86	0.300
Toluene	86	0.086
Water	32	0.320
	200	0.392

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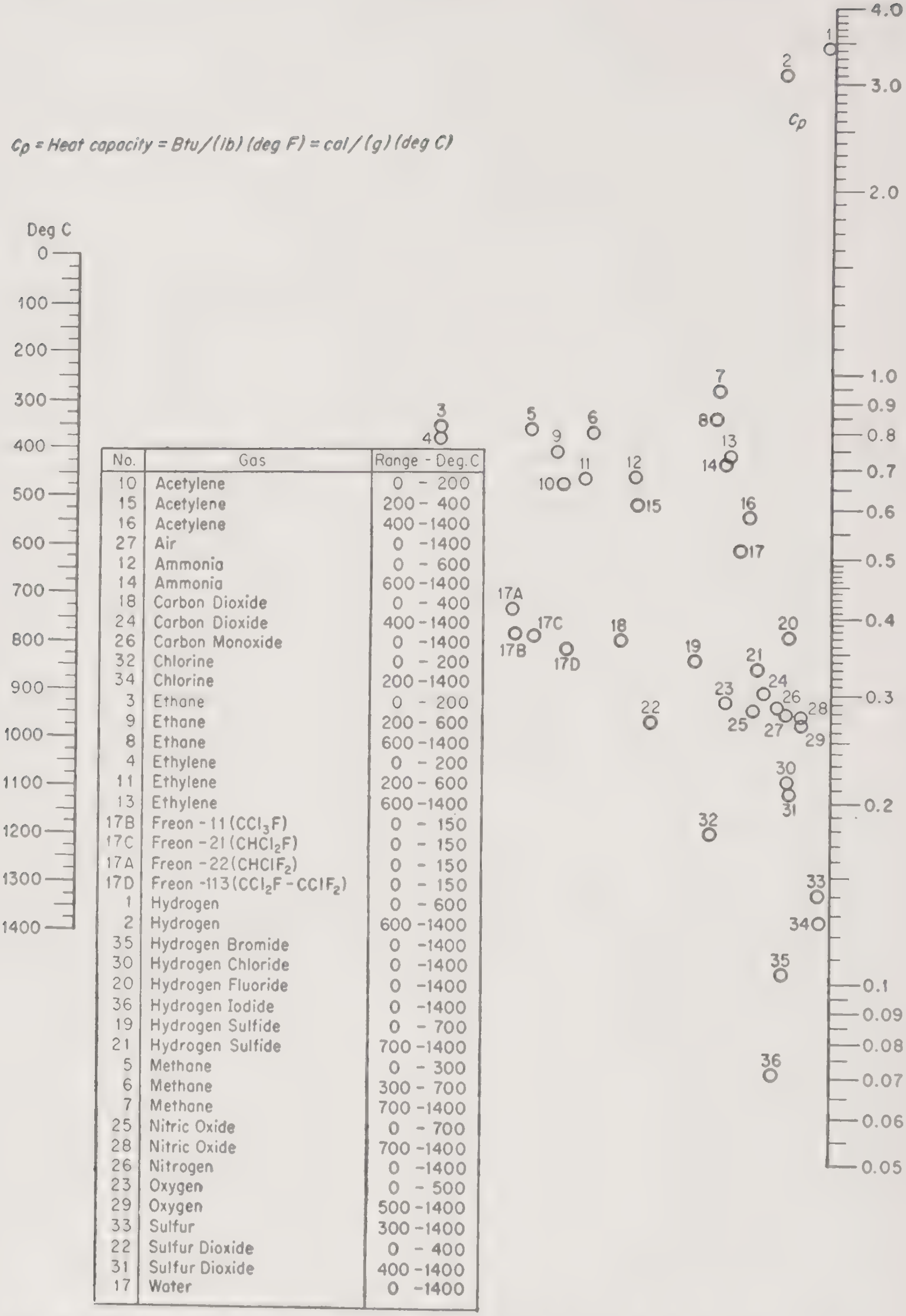
* J. H. Perry, "Chemical Engineers' Handbook," 3d ed., McGraw-Hill Book Company, Inc., New York, 1950.

TABLE 9. THERMAL CONDUCTIVITY OF GASES *

Gas	Temperature, °F	k, Btu/(hr)(sq ft)(°F/ft)
Air	32	0.0140
	212	0.0183
	392	0.0226
Ammonia	32	0.0128
	122	0.0157
Carbon dioxide	32	0.0085
	212	0.0133
Chlorine	32	0.0043
Hydrogen	32	0.100
	212	0.129
Methane	32	0.0175
	122	0.0215
Nitrogen	32	0.0140
	212	0.0180
Oxygen	32	0.0142
	212	0.0185
Sulfur dioxide	32	0.0050
	212	0.0069
Water vapor	200	0.0159
	600	0.0256

* J. H. Perry, "Chemical Engineers' Handbook," 3d ed., McGraw-Hill Book Company, Inc., New York, 1950.

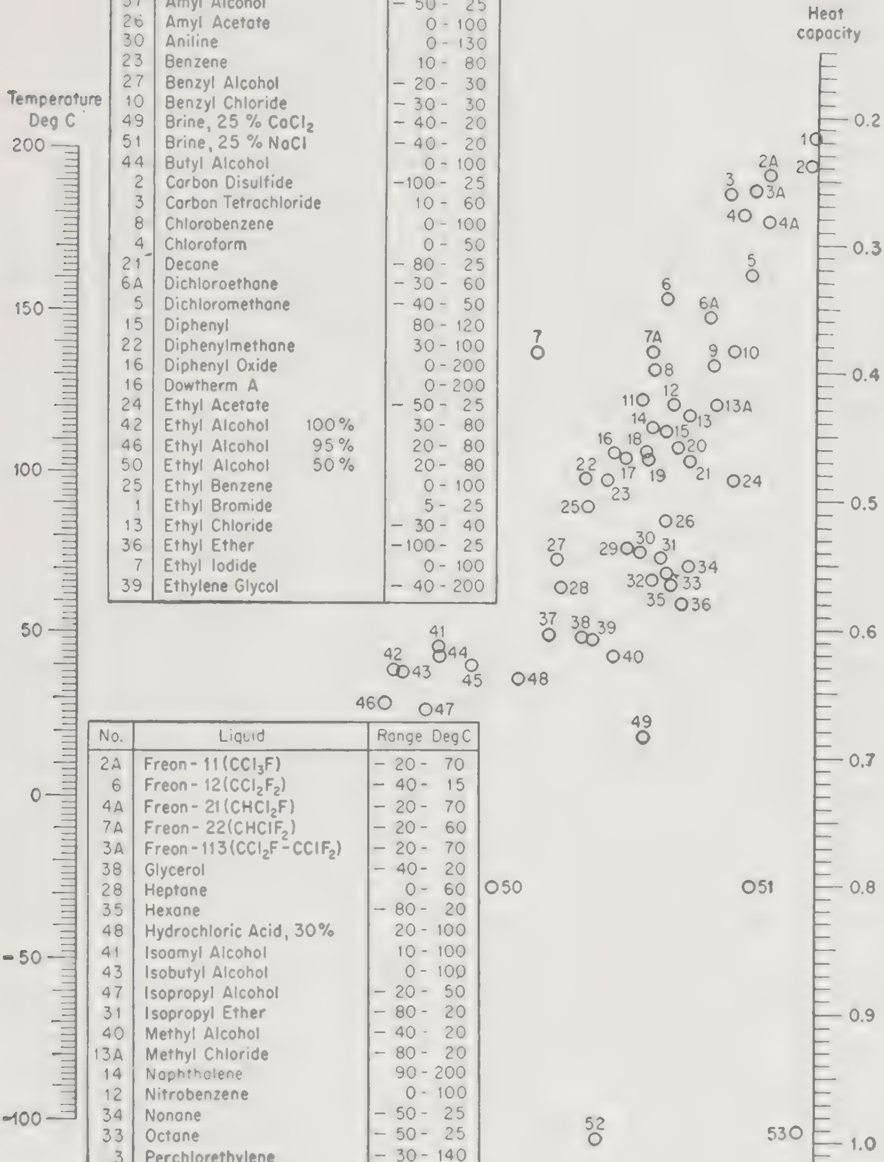


No.	Gas	Range - Deg. C
10	Acetylene	0 - 200
15	Acetylene	200 - 400
16	Acetylene	400 -1400
27	Air	0 -1400
12	Ammonia	0 - 600
14	Ammonia	600 -1400
18	Carbon Dioxide	0 - 400
24	Carbon Dioxide	400 -1400
26	Carbon Monoxide	0 -1400
32	Chlorine	0 - 200
34	Chlorine	200 -1400
3	Ethane	0 - 200
9	Ethane	200 - 600
8	Ethane	600 -1400
4	Ethylene	0 - 200
11	Ethylene	200 - 600
13	Ethylene	600 -1400
17B	Freon - 11 (CCl_3F)	0 - 150
17C	Freon - 21 ($CHCl_2F$)	0 - 150
17A	Freon - 22 ($CHClF_2$)	0 - 150
17D	Freon - 113 ($CCl_2F-CClF_2$)	0 - 150
1	Hydrogen	0 - 600
2	Hydrogen	600 -1400
35	Hydrogen Bromide	0 -1400
30	Hydrogen Chloride	0 -1400
20	Hydrogen Fluoride	0 -1400
36	Hydrogen Iodide	0 -1400
19	Hydrogen Sulfide	0 - 700
21	Hydrogen Sulfide	700 -1400
5	Methane	0 - 300
6	Methane	300 - 700
7	Methane	700 -1400
25	Nitric Oxide	0 - 700
28	Nitric Oxide	700 -1400
26	Nitrogen	0 -1400
23	Oxygen	0 - 500
29	Oxygen	500 -1400
33	Sulfur	300 -1400
22	Sulfur Dioxide	0 - 400
31	Sulfur Dioxide	400 -1400
17	Water	0 -1400

FIG. B-3. Heat capacities c_p of gases at 1 atm pressure. (*J. H. Perry, "Chemical Engineers' Handbook," 3d ed., McGraw-Hill Book Company, Inc., New York*, 1950.)

Heat capacity = Btu/(lb)(deg F) = cal/(g)(deg C)

No	Liquid	Range Deg C
29	Acetic Acid 100 %	0 - 80
32	Acetone	20 - 50
52	Ammonia	− 70 - 50
37	Amyl Alcohol	− 50 - 25
26	Amyl Acetate	0 - 100
30	Aniline	0 - 130
23	Benzene	10 - 80
27	Benzyl Alcohol	− 20 - 30
10	Benzyl Chloride	− 30 - 30
49	Brine, 25 % $CaCl_2$	− 40 - 20
51	Brine, 25 % NaCl	− 40 - 20
44	Butyl Alcohol	0 - 100
2	Carbon Disulfide	−100 - 25
3	Carbon Tetrachloride	10 - 60
8	Chlorobenzene	0 - 100
4	Chloroform	0 - 50
21	Decane	− 80 - 25
6A	Dichloroethane	− 30 - 60
5	Dichloromethane	− 40 - 50
15	Diphenyl	80 - 120
22	Diphenylmethane	30 - 100
16	Diphenyl Oxide	0 - 200
16	Dowtherm A	0 - 200
24	Ethyl Acetate	− 50 - 25
42	Ethyl Alcohol 100 %	30 - 80
46	Ethyl Alcohol 95 %	20 - 80
50	Ethyl Alcohol 50 %	20 - 80
25	Ethyl Benzene	0 - 100
1	Ethyl Bromide	5 - 25
13	Ethyl Chloride	− 30 - 40
36	Ethyl Ether	−100 - 25
7	Ethyl Iodide	0 - 100
39	Ethylene Glycol	− 40 - 200



No.	Liquid	Range Deg C
2A	Freon - 11 (CCl_3F)	− 20 - 70
6	Freon - 12 (CCl_2F_2)	− 40 - 15
4A	Freon - 21 ($CHCl_2F$)	− 20 - 70
7A	Freon - 22 ($CHClF_2$)	− 20 - 60
3A	Freon - 113 ($CCl_2F - CClF_2$)	− 20 - 70
38	Glycerol	− 40 - 20
28	Heptane	0 - 60
35	Hexane	− 80 - 20
48	Hydrochloric Acid, 30%	20 - 100
41	Isoamyl Alcohol	10 - 100
43	Isobutyl Alcohol	0 - 100
47	Isopropyl Alcohol	− 20 - 50
31	Isopropyl Ether	− 80 - 20
40	Methyl Alcohol	− 40 - 20
13A	Methyl Chloride	− 80 - 20
14	Naphthalene	90 - 200
12	Nitrobenzene	0 - 100
34	Nonane	− 50 - 25
33	Octane	− 50 - 25
3	Perchlorethylene	− 30 - 140
45	Propyl Alcohol	− 20 - 100
20	Pyridine	− 50 - 25
9	Sulfuric Acid 98%	10 - 45
11	Sulfur Dioxide	− 20 - 100
23	Toluene	0 - 60
53	Water	10 - 200
19	Xylene Ortho	0 - 100
18	Xylene Meta	0 - 100
17	Xylene Para	0 - 100

FIG. B-4. Heat capacities of liquids. (*J. H. Perry, "Chemical Engineers' Handbook," 3d ed., McGraw-Hill Book Company, Inc., New York*, 1950.)

TABLE 10. SPECIFIC GRAVITIES OF LIQUIDS *

The values presented in this table are based on the density of water at 4°C and a total pressure of 1 atm.

$$\text{Specific gravity} = \frac{\text{density of material at indicated temperature}}{\text{density of liquid water at } 4^\circ\text{C}}$$

Density of liquid water at 4°C = 1.000 g/cu cm = 62.43 lb/cu ft

Pure liquid	Formula	Temperature, °C	Specific gravity
Acetaldehyde	CH_3CHO	18	0.783
Acetic acid	CH_3CO_2H	0	1.067
		30	1.038
Acetone	CH_3COCH_3	20	0.792
Benzene	C_6H_6	20	0.879
n-Butyl alcohol	$C_2H_5CH_2CH_2OH$	20	0.810
Carbon tetrachloride	CCl_4	20	1.595
Ethyl alcohol	CH_3CH_2OH	10	0.798
		30	0.791
Ethyl ether	$(CH_3CH_2)_2O$	25	0.708
Ethylene glycol	$CH_2OH \cdot CH_2OH$	19	1.113
Glycerol	$CH_2OH \cdot CHOH \cdot CH_2OH$	15	1.264
		30	1.255
Isobutyl alcohol	$(CH_3)_2CHCH_2OH$	18	0.805
Isopropyl alcohol	$(CH_3)_2CHOH$	0	0.802
		30	0.777
Methyl alcohol	CH_3OH	0	0.810
		20	0.792
Nitric acid	HNO_3	10	1.531
		30	1.495
Phenol	C_6H_5OH	25	1.071
n-Propyl alcohol	$CH_3CH_2CH_2OH$	20	0.804
Sulfuric acid	H_2SO_4	10	1.841
		30	1.821
Water	H_2O	4	1.000
		100	0.958

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* J. H. Perry, "Chemical Engineers' Handbook," 3d ed., McGraw-Hill Book Company, Inc., New York, 1950.

TABLE 11. SPECIFIC GRAVITIES OF SOLIDS *

The specific gravities as indicated in this table apply at ordinary atmospheric temperatures. The values are based on the density of water at 4°C.

$$\text{Specific gravity} = \frac{\text{density of material}}{\text{density of liquid water at } 4^\circ\text{C}}$$

Density of liquid water at 4°C = 1.000 g/cu cm = 62.43 lb/cu ft

Substance	Specific gravity
Aluminum, hard-drawn	2.55–2.80
Brass, cast-rolled	8.4–8.7
Copper, cast-rolled	8.8–8.95
Glass, common	2.4–2.8
Gold, cast-hammered	19.25–19.35
Iron:	
Gray cast	7.03–7.13
Wrought	7.6–7.9
Lead	11.34
Nickel	8.9
Platinum, cast-hammered	21.5
Silver, cast-hammered	10.4–10.6
Steel, cold-drawn	7.83
Tin, cast-hammered	7.2–7.5
White oak timber, air-dried	0.77
White pine timber, air-dried	0.43
Zinc, cast-rolled	6.9–7.2

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* J. H. Perry, "Chemical Engineers' Handbook," 3d ed., McGraw-Hill Book Company. Inc., New York, 1950.

Table 12. Properties of Saturated Steam *

Values in table based on zero enthalpy of liquid water at 32°F

Temperature, °F	Absolute pressure, psi	Volume of vapor, cu ft/lb	Enthalpy		Latent heat of evaporation, Btu/lb
			Liquid, Btu/lb	Vapor, Btu/lb	
32	0.0885	3306	0.00	1075.8	1075.8
35	0.0999	2947	3.02	1077.1	1074.1
40	0.1217	2444	8.05	1079.3	1071.3
45	0.1475	2036.4	13.06	1081.5	1068.4
50	0.1781	1703.2	18.07	1083.7	1065.6
55	0.2141	1430.7	23.07	1085.8	1062.7
60	0.2563	1206.7	28.06	1088.0	1059.9
65	0.3056	1021.4	33.05	1090.2	1057.1
70	0.3631	867.9	38.04	1092.3	1054.3
75	0.4298	740.0	43.03	1094.5	1051.5
80	0.5069	633.1	48.02	1096.6	1048.6
85	0.5959	543.5	53.00	1098.8	1045.8
90	0.6982	468.0	57.99	1100.9	1042.9
95	0.8153	404.3	62.98	1103.1	1040.1
100	0.9492	350.4	67.97	1105.2	1037.2
105	1.1016	304.5	72.95	1107.3	1034.3
110	1.2748	265.4	77.94	1109.5	1031.6
115	1.4709	231.9	82.93	1111.6	1028.7
120	1.6924	203.27	87.92	1113.7	1025.8
125	1.9420	178.61	92.91	1115.8	1022.9
130	2.2225	157.34	97.90	1117.9	1020.0
135	2.5370	138.95	102.90	1119.9	1017.0
140	2.8886	123.01	107.89	1122.0	1014.1
145	3.281	109.15	112.89	1124.1	1011.2
150	3.718	97.07	117.89	1126.1	1008.2
155	4.203	86.52	122.89	1128.1	1005.2
160	4.741	77.29	127.89	1130.2	1002.3
165	5.335	69.19	132.89	1132.2	999.3
170	5.992	62.06	137.90	1134.2	996.3
175	6.715	55.78	142.91	1136.2	993.3

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* Abridged from "Thermodynamic Properties of Steam," by J. H. Keenan and F. G. Keyes, copyright, 1937, by Joseph H. Keenan and Frederick G. Keyes. Published by John Wiley & Sons, Inc., New York.

TABLE 12. PROPERTIES OF SATURATED STEAM (*Continued*)

Temperature, °F	Absolute pressure, psi	Volume of vapor, cu ft/lb	Enthalpy		Latent heat of evaporation, Btu/lb
			Liquid, Btu/lb	Vapor, Btu/lb	
180	7.510	50.23	147.92	1138.1	990.2
185	8.383	45.31	152.93	1140.1	987.2
190	9.339	40.96	157.95	1142.0	984.1
195	10.385	37.09	162.97	1144.0	981.0
200	11.526	33.64	167.99	1145.9	977.9
210	14.123	27.82	178.05	1149.7	971.6
212	14.696	26.80	180.07	1150.4	970.3
220	17.186	23.15	188.13	1153.4	965.2
230	20.780	19.382	198.23	1157.0	958.8
240	24.969	16.323	208.34	1160.5	952.2
250	29.825	13.821	218.48	1164.0	945.5
260	35.429	11.763	228.64	1167.3	938.7
270	41.858	10.061	238.84	1170.6	931.8
280	49.203	8.645	249.06	1173.8	924.7
290	57.556	7.461	259.31	1176.8	917.5
300	67.013	6.466	269.59	1179.7	910.1
310	77.68	5.626	279.92	1182.5	902.6
320	89.66	4.914	290.28	1185.2	894.9
330	103.06	4.307	300.68	1187.7	887.0
340	118.01	3.788	311.13	1190.1	879.0
350	134.63	3.342	321.63	1192.3	870.7
360	153.04	2.957	332.18	1194.4	862.2
370	173.37	2.625	342.79	1196.3	853.5
380	195.77	2.335	353.45	1198.1	844.6
390	220.37	2.0836	364.17	1199.6	835.4
400	247.31	1.8633	374.97	1201.0	826.0

TABLE 13. HEAT-EXCHANGER AND CONDENSER-TUBE DATA

Tube OD, in.	BWG	Wall thickness, in.	ID, in.	Flow area per tube, sq in.	Surface per lin ft, sq ft		Weight per lin ft, lb steel
					Outside	Inside	
½	12	0.109	0.282	0.0625	0.1309	0.0748	0.493
	14	0.083	0.334	0.0876	0.1309	0.0874	0.403
	16	0.065	0.370	0.1076	0.1309	0.0969	0.329
	18	0.049	0.402	0.127	0.1309	0.1052	0.258
	20	0.035	0.430	0.145	0.1309	0.1125	0.190
¾	10	0.134	0.482	0.182	0.1963	0.1263	0.965
	11	0.120	0.510	0.204	0.1963	0.1335	0.884
	12	0.109	0.532	0.223	0.1963	0.1393	0.817
	13	0.095	0.560	0.247	0.1963	0.1466	0.727
	14	0.083	0.584	0.268	0.1963	0.1529	0.647
	15	0.072	0.606	0.289	0.1963	0.1587	0.571
	16	0.065	0.620	0.302	0.1963	0.1623	0.520
	17	0.058	0.634	0.314	0.1963	0.1660	0.469
	18	0.049	0.652	0.334	0.1963	0.1707	0.401
1	8	0.165	0.670	0.335	0.2618	0.1754	1.61
	9	0.148	0.704	0.389	0.2618	0.1843	1.47
	10	0.134	0.732	0.421	0.2618	0.1916	1.36
	11	0.120	0.760	0.455	0.2618	0.1990	1.23
	12	0.109	0.782	0.479	0.2618	0.2048	1.14
	13	0.095	0.810	0.515	0.2618	0.2121	1.00
	14	0.083	0.834	0.546	0.2618	0.2183	0.890
	15	0.072	0.856	0.576	0.2618	0.2241	0.781
	16	0.065	0.870	0.594	0.2618	0.2277	0.710
	17	0.058	0.884	0.613	0.2618	0.2314	0.639
	18	0.049	0.902	0.639	0.2618	0.2361	0.545
1¼	8	0.165	0.920	0.665	0.3271	0.2409	2.09
	9	0.148	0.954	0.714	0.3271	0.2498	1.91
	10	0.134	0.982	0.757	0.3271	0.2572	1.75
	11	0.120	1.01	0.800	0.3271	0.2644	1.58
	12	0.109	1.03	0.836	0.3271	0.2701	1.45
	13	0.095	1.06	0.884	0.3271	0.2775	1.28
	14	0.083	1.08	0.923	0.3271	0.2839	1.13
	15	0.072	1.11	0.960	0.3271	0.2896	0.991
	16	0.065	1.12	0.985	0.3271	0.2932	0.900
	17	0.058	1.13	1.01	0.3271	0.2969	0.808
	18	0.049	1.15	1.04	0.3271	0.3015	0.688

TABLE 13. HEAT-EXCHANGER AND CONDENSER-TUBE DATA (*Continued*)

Tube OD, in.	BWG	Wall thickness, in.	ID, in.	Flow area per tube, sq in.	Surface per lin ft, sq ft		Weight per lin ft, lb steel
					Outside	Inside	
1½	8	0.165	1.17	1.075	0.3925	0.3063	2.57
	9	0.148	1.20	1.14	0.3925	0.3152	2.34
	10	0.134	1.23	1.19	0.3925	0.3225	2.14
	11	0.120	1.26	1.25	0.3925	0.3299	1.98
	12	0.109	1.28	1.29	0.3925	0.3356	1.77
	13	0.095	1.31	1.35	0.3925	0.3430	1.56
	14	0.083	1.33	1.40	0.3925	0.3492	1.37
	15	0.072	1.36	1.44	0.3925	0.3555	1.20
	16	0.065	1.37	1.47	0.3925	0.3587	1.09
	17	0.058	1.38	1.50	0.3925	0.3623	0.978
	18	0.049	1.40	1.54	0.3925	0.3670	0.831

TABLE 14. STEEL-PIPE DIMENSIONS

Nominal pipe size, in.	OD, in.	Schedule No.	ID, in.	Flow area per pipe, sq in.	Surface per lin ft, sq ft		Weight per lin ft, lb steel
					Outside	Inside	
⅛	0.405	40 *	0.269	0.058	0.106	0.070	0.25
		80 †	0.215	0.036	0.106	0.056	0.32
¼	0.540	40	0.364	0.104	0.141	0.095	0.43
		80	0.302	0.072	0.141	0.079	0.54
⅜	0.675	40	0.493	0.192	0.177	0.129	0.57
		80	0.423	0.141	0.177	0.111	0.74
½	0.840	40	0.622	0.304	0.220	0.163	0.85
		80	0.546	0.235	0.220	0.143	1.09
¾	1.05	40	0.824	0.534	0.275	0.216	1.13
		80	0.742	0.432	0.275	0.194	1.48
1	1.32	40	1.049	0.864	0.344	0.274	1.68
		80	0.957	0.718	0.344	0.250	2.17
1¼	1.66	40	1.380	1.50	0.435	0.362	2.28
		80	1.278	1.28	0.435	0.335	3.00
1½	1.90	40	1.610	2.04	0.498	0.422	2.72
		80	1.500	1.76	0.498	0.393	3.64
2	2.38	40	2.067	3.35	0.622	0.542	3.66
		80	1.939	2.95	0.622	0.508	5.03
2½	2.88	40	2.469	4.79	0.753	0.647	5.80
		80	2.323	4.23	0.753	0.609	7.67
3	3.50	40	3.068	7.38	0.917	0.804	7.58
		80	2.900	6.61	0.917	0.760	10.3
4	4.50	40	4.026	12.7	1.178	1.055	10.8
		80	3.826	11.5	1.178	1.002	15.0
6	6.625	40	6.065	28.9	1.734	1.590	19.0
		80	5.761	26.1	1.734	1.510	28.6
8	8.625	40	7.981	50.0	2.258	2.090	28.6
		80	7.625	45.7	2.258	2.000	43.4
10	10.75	40	10.02	78.8	2.814	2.62	40.5
		60	9.75	74.6	2.814	2.55	54.8
12	12.75	30	12.09	115	3.338	3.17	43.8
16	16.0	30	15.25	183	4.189	4.00	62.6
20	20.0	20	19.25	291	5.236	5.05	78.6
24	24.0	20	23.25	425	6.283	6.09	94.7

* Schedule 40 designates former "standard" pipe.

† Schedule 80 designates former "extra-strong" pipe.

TABLE 15. INTERNATIONAL ATOMIC WEIGHTS *

Substance	Symbol	Atomic weight	At. no.	Substance	Symbol	Atomic weight	At. no.
Actinium	Ac	227	89	Molybdenum	Mo	95.95	42
Aluminum	Al	26.98	13	Neodymium	Nd	144.27	60
Americium	Am	243	95	Neon	Ne	20.183	10
Antimony	Sb	121.76	51	Neptunium	Np	237	93
Argon	A	39.944	18	Nickel	Ni	58.71	28
Arsenic	As	74.91	33	Niobium	Nb	92.91	41
Astatine	At	210	85	Nitrogen	N	14.008	7
Barium	Ba	137.36	56	Osmium	Os	190.2	76
Berkelium	Bk	249	97	Oxygen	O	**16**	8
Beryllium	Be	9.013	4	Palladium	Pd	106.4	46
Bismuth	Bi	209.00	83	Phosphorus	P	30.975	15
Boron	B	10.82	5	Platinum	Pt	195.09	78
Bromine	Br	79.916	35	Plutonium	Pu	242	94
Cadmium	Cd	112.41	48	Polonium	Po	210	84
Calcium	Ca	40.08	20	Potassium	K	39.100	19
Californium	Cf	249	98	Praseodymium	Pr	140.92	59
Carbon	C	12.011	6	Promethium	Pm	145	61
Cerium	Ce	140.13	58	Protactinium	Pa	231	91
Cesium	Cs	132.91	55	Radium	Ra	226.05	88
Chlorine	Cl	35.457	17	Radon	Rn	222	86
Chromium	Cr	52.01	24	Rhenium	Re	186.22	75
Cobalt	Co	58.94	27	Rhodium	Rh	102.91	45
Copper	Cu	63.54	29	Rubidium	Rb	85.48	37
Curium	Cm	245	96	Ruthenium	Ru	101.1	44
Dysprosium	Dy	162.51	66	Samarium	Sm	150.35	62
Erbium	Er	167.27	68	Scandium	Sc	44.96	21
Europium	Eu	152.0	63	Selenium	Se	78.96	34
Fluorine	F	19.00	9	Silicon	Si	28.09	14
Francium	Fr	223	87	Silver	Ag	107.880	47
Gadolinium	Gd	157.26	64	Sodium	Na	22.991	11
Gallium	Ga	69.72	31	Strontium	Sr	87.63	38
Germanium	Ge	72.60	32	Sulfur	S	32.066	16
Gold	Au	197.2	79	Tantalum	Ta	180.95	73
Hafnium	Hf	178.50	72	Technetium	Tc	99	43
Helium	He	4.003	2	Tellurium	Te	127.61	52
Holmium	Ho	164.94	67	Terbium	Tb	158.93	65
Hydrogen	H	1.0080	1	Thallium	Tl	204.39	81
Indium	In	114.82	49	Thorium	Th	232.05	90
Iodine	I	126.91	53	Thulium	Tm	168.94	69
Iridium	Ir	193.2	77	Tin	Sn	118.70	50
Iron	Fe	55.85	26	Titanium	Ti	47.90	22
Krypton	Kr	83.80	36	Tungsten (wolfram)	W	183.86	74
Lanthanum	La	138.92	57	Uranium	U	238.07	92
Lead	Pb	207.21	82	Vanadium	V	50.95	23
Lithium	Li	6.940	3	Xenon	Xe	131.30	54
Lutetium	Lu	174.99	71	Ytterbium	Yb	173.04	70
Magnesium	Mg	24.32	12	Yttrium	Y	88.92	39
Manganese	Mn	54.94	25	Zinc	Zn	65.38	30
Mercury	Hg	200.61	80	Zirconium	Zr	91.22	40

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